UNIVERSITY OF ALBERTA

ICHNOLOGICAL AND SEDIMENTOLOGICAL FACIES ANALYSIS OF THE DOE CREEK MEMBER OF THE KASKAPAU FORMATION, NORTHWEST ALBERTA, CANADA.

BY

SCOTT ALEXANDER REID ©

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of the requirements for the degree of Master of Science

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ABSTRACT

The Cenomanian Doe Creek Member of the Kaskapau Formation in northwest Alberta comprises a series of retrogradationally stacked, northeast-southwest trending shoreline deposits. The sandstones are interpreted to have been deposited as lowstand delta and/or shoreface systems caused by smaller-scale oscillations in sea-level during an overall transgression.

An integrated ichnological and sedimentological analysis of fifty-five core examined from the study area exhibited eleven facies grouped into two facies associations. Facies association one comprised deposits from a progradational, open-marine shoreface and facies association two originated from a prograding deltaic coast. The facies architecture of the Doe Creek Member highlights complexities induced by deltaic influences on a given shoreline. Sandstone thickness, sedimentology, and ichnological character varies along depositional strike stemming from proximity to deltaic point sources. Based on these observations, an ichnological model for the recognition of deltaic deposits was generated which allows for much more accurate characterizations of ancient shoreline systems.

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TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION, RESEARCH RATIONALE, OBJECTIVES, STUDY AREA, AND METHODOLOGY 1
- 1.1 INTRODUCTION 1
- 1.2 RESEARCH RATIONALE 1
- 1.3 OBJECTIVES 2
- 1.4 STUDY AREA AND METHODOLOGY 2

CHAPTER 2

TECTONIC SETTING, STRATIGRAPHIC RELATIONS, PALEOGEOGRAPHY, AND PREVIOUS WORK 5
- 2.1 TECTONIC SETTING 5
  - 2.1.1 THE WESTERN CANADIAN SEDIMENTARY BASIN 5
  - 2.1.2 THE PEACE RIVER ARCH 7
- 2.2 BIOSTRATIGRAPHY AND AGE 9
- 2.3 STRATIGRAPHIC RELATIONSHIPS 12
- 2.3 PALEOGEOGRAPHY 15
- 2.4 PREVIOUS WORK 17

CHAPTER 3

FACIES ANALYSIS AND FACIES ASSOCIATIONS 18
- 3.1 INTRODUCTION 18
- 3.2 FACIES DESCRIPTIONS AND INTERPRETATION 21
  - 3.2.1 FACIES 1A: DARK GREY TO BLACK CLAYSTONES AND MUDSTONES 21
  - 3.2.2 FACIES 1B: MODERATELY BIOTURBATED SILTY MUDSTONE 24
  - 3.2.3 FACIES 2: PERVASIVELY BIOTURBATED SANDY MUDSTONE AND SILTSTONE 27
  - 3.2.4 FACIES 3: PERVASIVELY BIOTURBATED MUDDY SANDSTONE AND SILTY SANDSTONE 32
  - 3.2.5 FACIES 4: INTERLAMINATED MUDSTONE, SILTSTONE, AND SANDSTONE 39
  - 3.2.6 FACIES 5: INTERBEDDED SANDSTONE, CLAYSTONE, AND SILTSTONE 45
  - 3.2.7 FACIES 6: INTERBEDDED SANDSTONE, BIOTURBATED SANDSTONE, AND CLAYSTONE 51
  - 3.2.8 FACIES 7A: THICKLY BEDDED, LAMINATED SANDSTONE 58
  - 3.2.9 FACIES 7B: LAMINATED TO STRUCTURELESS, DEFORMED SANDSTONE 67
  - 3.2.10 FACIES 8: INTERBEDDED, BIOTURBATED SANDSTONE AND LAMINATED SANDSTONE 72
  - 3.2.11 FACIES 9: MODERATELY BIOTURBATED, LAMINATED SANDSTONE 77
  - 3.2.12 FACIES 10: LARGE-SCALE, CROSS-BEDDED SANDSTONE 80
  - 3.2.13 FACIES 11:SPARSELY BIOTURBATED MUDSTONE 84
- 3.3 FACIES ASSOCIATIONS 87

CHAPTER 4

STRATIGRAPHIC AND DEPOSITIONAL MODEL........ 88
- 4.1 INTRODUCTION........ 88
- 4.2 MAPS........ 88
- 4.3 CROSS SECTIONS........ 92
- 4.4 STRATIGRAPHIC EVOLUTION OF THE DOE CREEK MEMBER........ 103
- 4.5 DEPOSITIONAL MODEL........ 107

CHAPTER 5

RECOGNIZING SUBAQEOUS DELTA SUCCESSIONS

- 5.1 INTRODUCTION AND BACKGROUND........ 111
- 5.2 THE OFFSHORE........ 114
- 5.3 THE PRODELTA........ 116
- 5.4 ICHNOLOGICAL MODEL OF THE OFFHORE AND PRODELTA........ 120

CHAPTER 6

CONCLUSIONS........ 123

REFERENCES........ 124

APPENDIX........ 139

LIST OF TABLES

CHAPTER 2

TABLE 2.1. BIOSTRATIGRAPHIC ZONES.. 10

CHAPTER 3

TABLE 3.1. SHOREFACE MODEL.. 19
TABLE 3.2. GRAIN SIZE TABLE.. 20

LIST OF FIGURES

CHAPTER 1

FIGURE 1.1. STUDY AREA........ 4

CHAPTER 2

FIGURE 2.1. FORELAND BASIN TECTONICS........ 5
FIGURE 2.2. TERRANE MAP OF THE CANADIAN CORDILLERA........ 6
FIGURE 2.3. THE PEACE RIVER ARCH........ 7
FIGURE 2.4. TECTONIC DOMAINS OF THE ALBERTA BASEMENT........ 8
FIGURE 2.5. STRATIGRAPHIC CHART........ 12
FIGURE 2.6. DUNVEGAN AND KASKAPAU STRATIGRAPHY........ 13
FIGURE 2.7. TYPE WELL LOGS........ 14
FIGUIRE 2.8. PALEOGEOGRAPHY........ 15
FIGURE 2.9. DUNVEGAN PALEOGEOGRAPHY........ 16

CHAPTER 3

FIGURE 3.1 FACIES 1A........ 23
FIGURE 3.2 FACIES 1B........ 26
FIGURE 3.3 FACIES 2........ 29
FIGURE 3.4 FACIES 2........ 31
FIGURE 3.5 FACIES 3........ 35
FIGURE 3.6. FACIES 3........ 37
FIGURE 3.7. FACIES 4........ 41
FIGURE 3.8. FACIES 4........ 43
FIGURE 3.9. FACIES 5........ 48
FIGURE 3.10. FACIES 5........ 50
FIGURE 3.11. FACIES 6........ 54
FIGURE 3.12. FACIES 6........ 56
FIGURE 3.13. FACIES 7A........ 61
FIGURE 3.14. FACIES 7A........ 63
FIGURE 3.15. FACIES 7A........ 65
FIGURE 3.16. FACIES 7B........ 70
FIGURE 3.17. FACIES 8........ 74
FIGURE 3.18. FACIES 8........ 76
FIGURE 3.19. FACIES 9........ 79
FIGURE 3.20. FACIES 10........ 83
FIGURE 3.21. FACIES 11........ 86

CHAPTER 4

FIGURE 4.1 NET SAND ISOPACH OF THE DOE CREEK "I" SANDSTONE........ 90
FIGURE 4.1 NET SAND ISOPACH OF THE DOE CREEK "A" SANDSTONE........ 91

Figure 4.3. Well log cross section A-A' 94
Figure 4.4. Core cross section A-A' 95
Figure 4.5. Well log cross section B-B' 97
Figure 4.6. Core cross section B-B' 98
Figure 4.7. Well log cross section C-C' 101
Figure 4.8. Core cross section C-C' 102
Figure 4.9. Incised shoreface model 104
Figure 4.10. Doe Creek Member Stratigraphy 105
Figure 4.11. Mixed offshore - prodelta facies 109
Figure 4.12. Doe Creek Member depositional model 110

Chapter 5

Figure 5.1. Tripartite classificaton of deltas 112
Figure 5.2. Schematic illustration of the *Cruziana* Ichnofacies 114
Figure 5.3. Deltaic and Shoreface subenvironments 117
Figure 5.4. Schematic illustration of *Zoophycos* 118
Figure 5.5. Doe Creek Member *Zoophycos* 119
Figure 5.6. Offshore versus Prodelta 121

CHAPTER ONE

INTRODUCTION, RATIONALE FOR RESEARCH, OBJECTIVES, STUDY AREA, AND METHODOLOGY

1.1 INTRODUCTION

This study was undertaken with aims to provide a detailed sedimentological and ichnological description and interpretation of the Upper Cretaceous (Cenomanian) Doe Creek Member of the Kaskapau Formation in northwest Alberta. The body of published literature on the Doe Creek Member is relatively sparse, including local studies of the internal stratigraphy, sedimentology and petroleum geology of the Doe Creek Member in Valhalla Field in northwest Alberta (Wallace-Dudley and Leckie; 1988,1993,and 1995), regional stratigraphic studies of the Shaftesbury, Dunvegan, and Kaskapau Formations (Bhattacharya and Walker, 1991a; Plint, 2000; Varban and Plint, 2005) and an investigation of the petroleum geology and reservoir exploitation of the Doe Creek "I" pool in Valhalla Field (Hogg *et al.,* 1998). To date, an integrated ichnological and sedimentological facies analysis of the Doe Creek Member has not been undertaken.

The methodology by which ichnological analysis is incorporated with sedimentological analysis, has been employed successfully on numerous stratigraphic intervals in the Western Canadian Sedimentary Basin, and has proven invaluable in the development of accurate depositional models. This information is vital to accurate facies-based evaluation of paleoenvironments within the succession. The core-based data and interpretation can then be integrated within a stratigraphic framework to develop a depositional and stratigraphic model to explain the genesis of the Doe Creek Member within the study area. Resultant understanding of the depositional system will facilitate an enhanced characterization of reservoir units within the Doe Creek Member which will assist in the future exploration and exploitation methodologies.

1.2 RESEARCH RATIONALE

The Kaskapau Formation is comprised predominantly of open marine mudstones and shales deposited during the late Cenomanian to mid Turonian. Within the broadly transgressive marine deposits discrete, isolated, shallow-marine sandstone bodies represent an enigmatic feature of the depositional system. The isolated sandstones within the Doe Creek Member are prolific hydrocarbon producers in the Peace River area of northwest Alberta, hosting an estimated 570 million barrels (initial volume in place) of sweet, light gravity (~37 API) oil and are a highly sought target for natural gas in the Alberta Deep Basin and British Columbia. Despite the high economic impact of the Doe Creek Member, it remains an understudied and poorly understood horizon.

Since the mid-1980's, there has been ongoing development of an integrated ichnologic and sedimentologic model for marginal and shallow marine sandstones of the Cretaceous Western Interior. Numerous studies on key stratigraphic intervals such as the Viking, Cardium, McMurray, Peace River, Spirit River, and Dunvegan Formations in Alberta have proven that integration of ichnology with sedimentology is fundamental to the interpretation of ancient sedimentary deposits. However, such a study has not been undertaken on the Doe Creek Member. This study will address the need for a detailed, integrated ichnologic and sedimentologic facies analysis on the Doe Creek Member and provide an accurate interpretation of paleoenvironments. A corollary to this research will be a contribution to the field of integrated ichnologic-sedimentologic facies analysis with new data, observations and interpretations on deposits which have not previously been studied thusly.

1.3. OBJECTIVES

This study has two primary objectives. The first is to provide a detailed and comprehensive analysis of sedimentary facies encountered in the Doe Creek Member. The facies analysis will provide an accurate interpretation of paleoenvironments and depositional processes active during deposition. The second is to place the sedimentary facies in a stratigraphic framework to establish a paleogeographic and stratigraphic evolution of the Doe Creek Member. Significant ichnological and sedimentological deviations from established facies models were noted in the ichnological assemblages in several facies within the Doe Creek Member, particularly in the offshore facies. These perturbations were interpreted to reflect the influence of deltaic sedimentation on the resident biota active during deposition. A secondary objective of this thesis is to develop a model for use in identifying ancient deltas in the rock record based on the data gathered on non-deltaic and deltaic facies within the Doe Creek Member.

1.4 STUDY AREA AND METHODOLOGY

The selection of the study area for this project took into consideration two key requirements. There must be sufficient core and well control to allow for meaningful evaluation and it should be located in an area that will provide a tangible benefit for petroleum exploration and exploitation. The study area focuses on the subsurface expression of the Doe Creek Member in Valhalla field and surrounding area, northwestern Alberta (Figure 1.1). The study area covers approximately 2000 square kilometers, encompassing townships 71 to 79 and ranges 6 to 13 west of the sixth meridian. Wide-ranging hydrocarbon exploration targeting primarily Triassic strata in this area lead to the discovery of the Valhalla Doe Creek "I" pool in 1979 (Hogg *et al.*, 1998). This precipitated an aggressive exploration and exploitation strategy pursuing the Doe Creek Member resulting in numerous, tightly-spaced geophysical well logs and a large number of cores. The majority of cores available are relatively short intervals (<10 m) within the boundaries of the Doe Creek "I" pool. However, subsequent drilling in the surrounding area generated good core control over the study area. In this study, fifty-five cored intervals (see Fig.1.1 for locations) from the Doe Creek Member, totaling approximately 960 meters in length, were analyzed.

The facies analysis of the Doe Creek Member was accomplished by the evaluation of cores retrieved from well bores within the study area. The ichnological analysis included identification of ichnogenera, relative abundance of total trace fossil occurrence (bioturbation intensity), trace fossil size, and diversity of the ichnological suites. Sedimentological analysis focused on features such as lithology, grain-size, primary sedimentary structures, bedding contacts and styles, bed thickness, and penecontemporaneous deformation structures. Accompanying these core data, 320 gamma-ray well logs were used to generate isopach maps of the prevalent sandstones in the study area. Cross-sections were generated utilizing well logs to evaluate the sequence stratigraphy in the area and place the core data in stratigraphic context. Well log evaluation and correlation was conducted by hand, the maps and cross sections presented herein were digitized for ease of presentation.

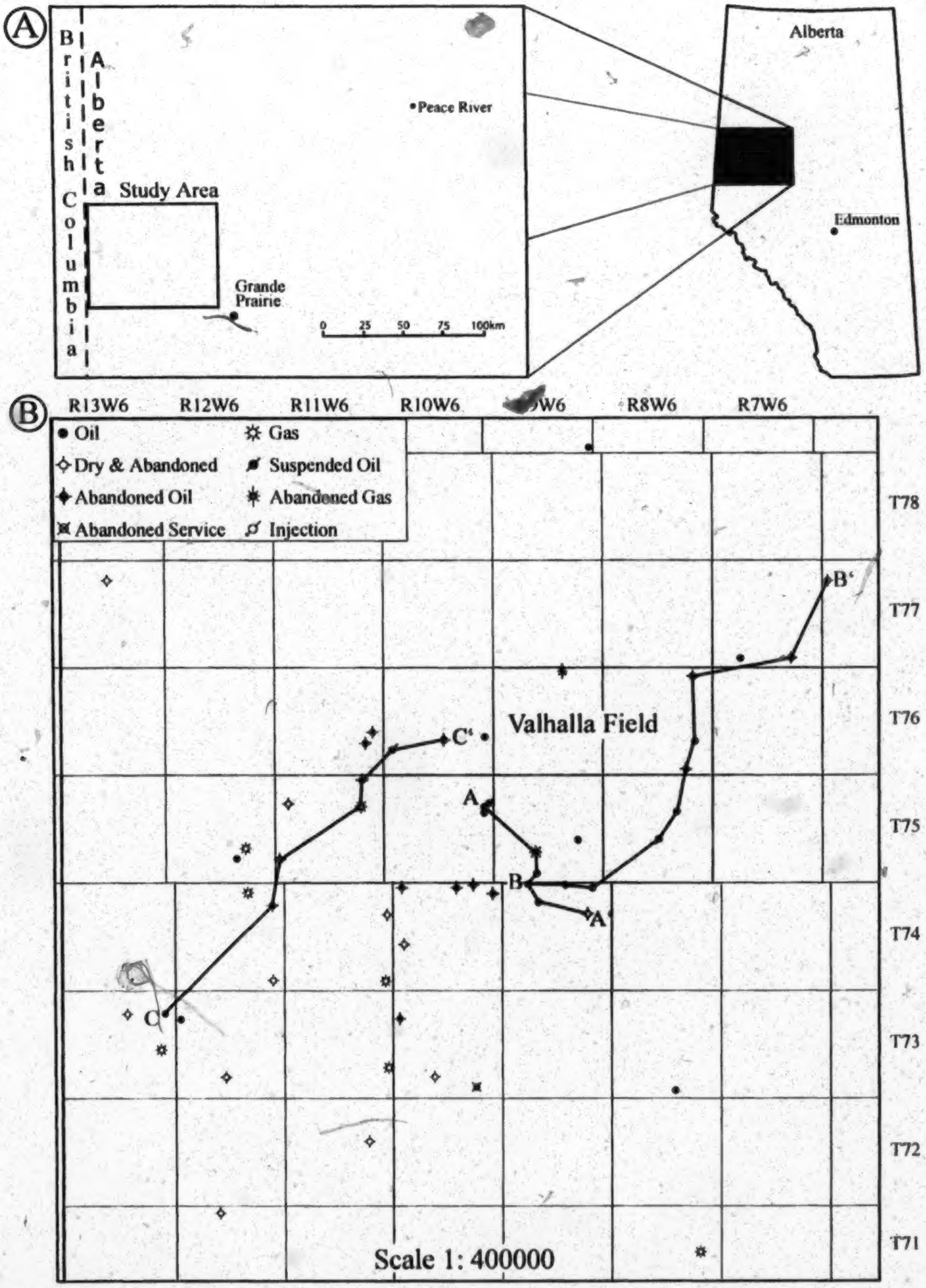

A
British Columbia
Alberta
Study Area
Peace River
Grande Prairie
0 25 50 75 100km
Alberta
Edmonton
B
R13W6
R12W6
R11W6
R10W6
W6
R8W6
R7W6
● Oil
◇ Dry & Abandoned
✦ Abandoned Oil
Abandoned Service
Gas
Suspended Oil
Abandoned Gas
Injection
T78
T77
T76
T75
T74
T73
T72
T71
B'
C'
Valhalla Field
A
B
A'
C
Scale 1: 400000

Figure 1.1. Study Area. **(A)** map of Alberta showing the location of the study area. **(B)**. Detailed map of study area with locations of logged core shown; Valhalla field and cross section lines are also annotated.

CHAPTER 2

TECTONIC SETTING, STRATIGRAPHY, PALEOGEOGRAPHY, AND PREVIOUS WORK.

2.1 TECTONIC SETTING

2.1.1 THE WESTERN CANADIAN SEDIMENTARY BASIN

The Western Canadian Sedimentary Basin (WCSB) comprises a succession of Paleozoic passive margin deposits, and Middle Jurassic-Eocene foreland basin deposits. Dickinson (1974) defined a foreland basin as a basin on a continental platform associated with major compressional zones of deformation, introducing the terms "peripheral" and "retroarc" foreland basin. Peripheral foreland basins form within the arc-trench gap of the orogen during continent-continent collisions, whereas retroarc foreland basins form in front of the thrust belt in response to tectonic loading. This type of basin-forming process results in an asymmetric depression created by flexure of the lithosphere in response to the stress of an adjacent thrust belt, which also acts as the predominant sediment source for foreland basin fill (Figure 2.1). The Middle Jurassic to Eocene span of the WCSB is characterized as a retroarc foreland basin (Dickinson, 1974). The transition from passive margin to foreland basin setting is thought to be the result of accretion of

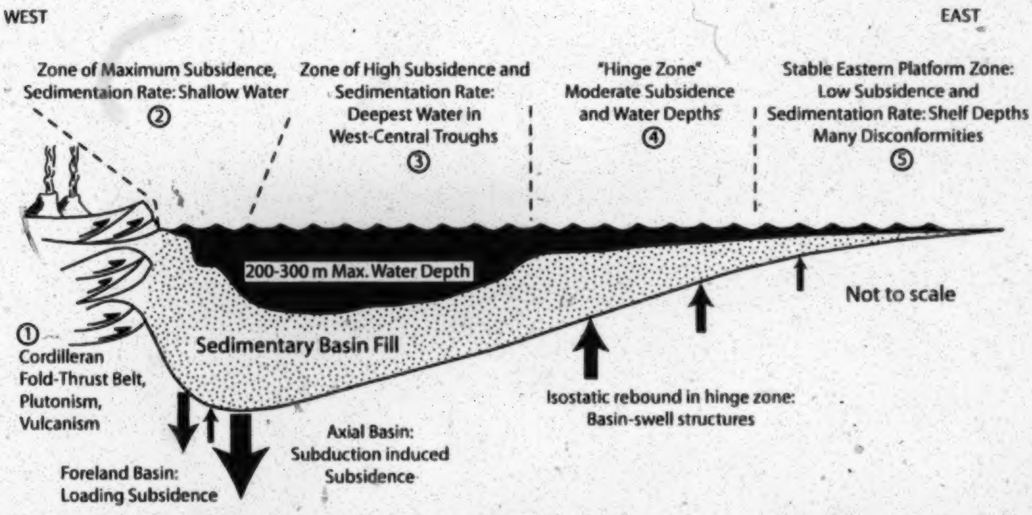

WEST
EAST
Zone of Maximum Subsidence, Sedimentaion Rate: Shallow Water ②
Zone of High Subsidence and Sedimentation Rate: Deepest Water in West-Central Troughs ③
"Hinge Zone" Moderate Subsidence and Water Depths ④
Stable Eastern Platform Zone: Low Subsidence and Sedimentation Rate: Shelf Depths Many Disconformities ⑤
200-300 m Max. Water Depth
Not to scale
Sedimentary Basin Fill
① Cordilleran Fold-Thrust Belt, Plutonism, Vulcanism
Foreland Basin: Loading Subsidence
Axial Basin: Subduction induced Subsidence
Isostatic rebound in hinge zone: Basin-swell structures

Figure 2.1. Foreland basin tectonics. Idealized cross section across the Western Canada foreland basin at maximum transgression. The positions, directions, and sizes of arrows indicate tectonic forces active. (Modified from Kauffman, 1984; Leckie and Smith, 1992).

allochthonous terranes on the Pacific margin of the ancient North American Continent. The compressional forces induced by terrane accretion caused tectonic shortening and thickening of the continental lithosphere via imbrication and tectonic progradation of thrust slices (Price, 1973; Beaumont, 1981; Cant, 1989). The foreland basin is elongated parallel to orogenic belt, with preserved Mesozoic strata terminating at approximately 62°N and the underlying, passive-margin Paleozoic strata crop out (Figure 2.2). Regional tectonic influence played a major role in the sedimentation styles, patterns, and distributions within Doe Creek Member of the Kaskapau Formation primarily by affecting basin morphology. However, the study area of this project lies to the east of the deformation front of the Cordillera, and stratigraphic analysis of the Doe Creek Member within indicates no major structural disturbances relating to the compressional tectonics of the foreland basin (*e.g.* fault repetition, folding).

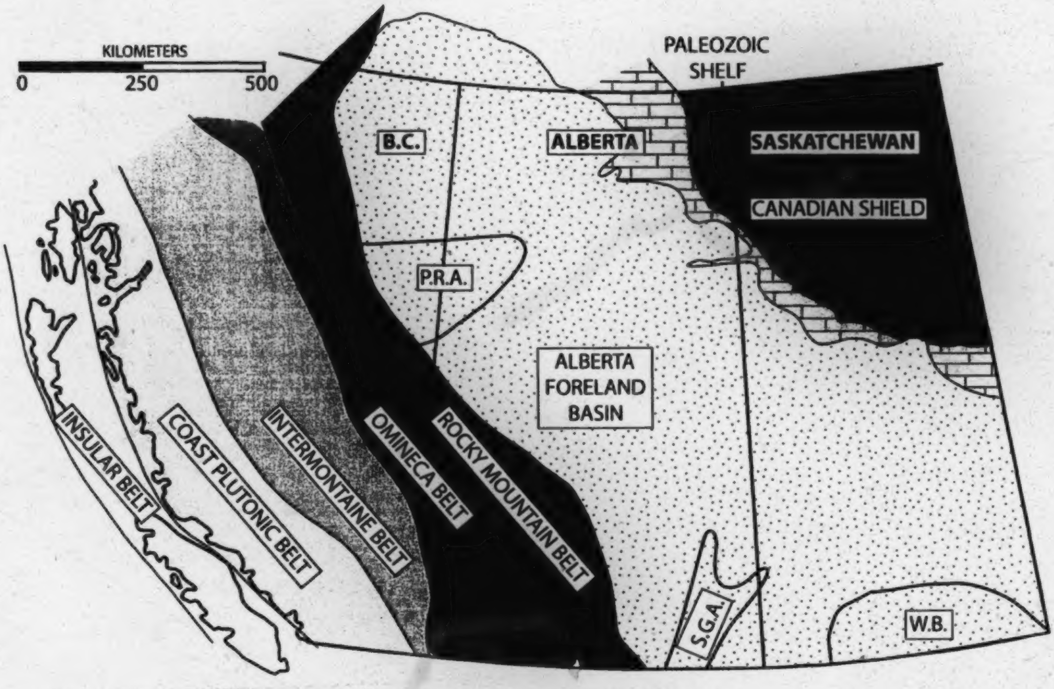

KILOMETERS
0
250
500
PALEOZOIC SHELF
B.C.
ALBERTA
SASKATCHEWAN
CANADIAN SHIELD
P.R.A.
ALBERTA FORELAND BASIN
INSULAR BELT
COAST PLUTONIC BELT
INTERMONTAINE BELT
OMINECA BELT
ROCKY MOUNTAIN BELT
S.G.A.
W.B.

Figure 2.2. Terrane map of the Canadian Cordillera. The approximate edge of foreland basin fill is annotated. P.R.A.: Peace River Arch, S.G.A.: Sweetgrass Arch, W.B.: Williston basin. (modified from Cant, 1989).

2.1.2 THE PEACE RIVER ARCH

The Peace River Arch (PRA) was one of the most prominent tectonic elements in the Western Canadian Sedimentary Basin during the Phanerozoic (Figure2.3). The Arch's history is complex having been both a topographically positive and negative feature over time, profoundly affecting sedimentation patterns in the Peace River area. The PRA is a Precambrian basement uplift with up to 1000m of relief trending east-northeast to west-southwest. It is 140 km wide and extends approximately 750 km along its axis (Cant, 1988). The crystalline basement of the PRA is subdivided by magnetic and isotopic age data (discussed in Ross *et al.*, 1991) into distinct tectonic domains (Figure 2.4).

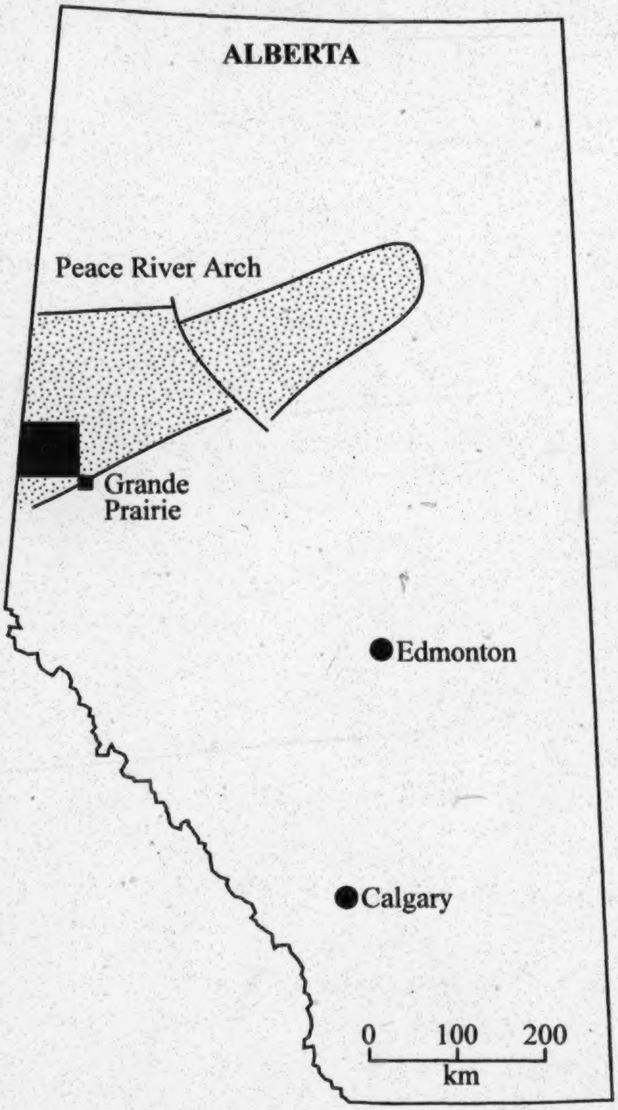
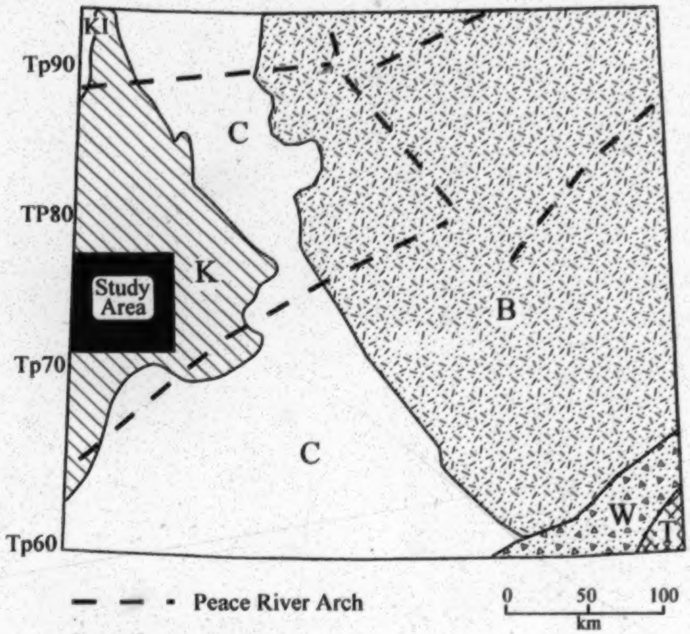


Figure 2.3. Peace River Arch. Map showing the approximate outline of the Peace River Arch in Alberta. After Donaldson *et al.* (1999)



Legend

K - Knitsuan
C - Chinchaga
B - Buffalo Head
KI - Kiskatinaw
T - Thorsby
W - Wabamun

Figure 2.4. Tectonic domains of the Alberta basement, after Ross (1990).

The tectonic evolution of the PRA has been subdivided into three phases spanning the Phanerozoic (Cant, 1988; O'Connell *et al.*, 1990). The first phase of development of the PRA consists of uplift, faulting, and onlap lasting until the mid-Devonian. The initiation of PRA uplift has been estimated between latest Proterozoic and middle Cambrian. Cant (1988) noted the Elk Point Group onlapped onto the margins of the PRA, while recent work by Eaton *et al.* (1999) suggests onlap occurred during the Cambro-Ordovician based on Lithoprobe data. In the interceding time, the PRA was a topographic high relative to surrounding regions of the WCSB. The second phase of PRA evolution is characterized by enhanced subsidence caused by block subsidence and faulting, resulting in the formation of the Peace River Embayment (PRE). The localized subsidence within the PRE was associated with a complex system of nested grabens termed the Dawson Creek Graben Complex (DCGC) which profoundly effected sedimentation patterns of Carboniferous through Triassic strata (Barclay *et al.*, 1990). The third phase of PRA evolution was characterized by regional enhanced subsidence, and was coeval with the initiation of thrust loading (Columbian and Laramide orogenies) in the Cordillera (O'Connel *et al*., 1990, Eaton *et al*., 1999).

Hart and Plint (1990) proposed a fourth phase of PRA evolution inferring that uplift of the PRA caused northward thinning of the Turonian Cardium Formation. Donaldson *et al*. (1998, 1999) proposed a combination of uplift associated with a forebulge and reactivation of the PRA to explain sedimentation patterns observed in the Coniacian Bad Heart Formation. Kreitner (2001) reported non-marine strata and northward thinning of the Lower Kaskapau Formation along the Peace River, attributing these phenomena as a possible uplift of the PRA.

Several theories have been put forward to explain the cause and evolution of the complex basement feature. The uplift of the first phase of PRA development has been attributed to: 1) potassium metasomatism induced by mantle plume activity causing isostatic uplift (Burwash and Krupicka, 1969, 1970; Burwash *et al*., 1973; Stelck *et al.*, 1978), 2) a failed rift system extending into the continent from the Proto-Pacific ocean (Cant, 1988; Cant and O'Connell, 1988), 3) a focused flexural response to Late Proterozoic or early Paleozoic loading of the rifted continental margin and yoking with the Williston Basin (Beaumont *et al.,* 1993), 4) the continental extension of an oceanic fracture zone (O'Connell *et al*., 1990, O'Connell, 1994), 5) anomalous stress build-ups and elastic deflections generated by a combination of the presence of diabase sheets and the break-up and formation of the paleoPacific margin (Eaton *et al*., 1999). The formation and subsidence of the DCGC are thought to be the result of extension related to an incipient rift possibly related to the Antler orogeny (O'Connell *et al*., 1990, O'Connell, 1994; Barclay *et al.,* 1990). The third phase of enhanced subsidence during the Jurassic and Cretaceous was likely a response to regional thrust sheet loading and subsequent downwarping of the craton.

2.2 BIOSTRATIGRAPHY AND AGE

The Kaskapau Formation is late Cenomanian to mid Turonian in age. Various time spans have been postulated for the Cenomanian including 90-94 Ma (Obradovich and Cobban, 1975); 91.5-96 Ma (Fouch, *et al.*, 1982); 92-96 Ma (Haq *et al.*, 1988); 91-93.5 Ma (Caldwell *et al.*, 1993); and 93.3-98.5 Ma (Obradovich, 1993). The dates vary somewhat, however there is generally a good agreement between the authors that the duration of the Cenomanian was approximately 4 million years. The lower Kaskapau is situated entirely within the *Verneuilinoides perplexus* Zone (table 2.1) which is considered to be of Late Cenomanian age (Stelck and Wall, 1955; Caldwell *et*

PERIOD	STAGES	SELECTED MOLLUSCAN INDICES	FORAMINIFERAL	
			ZONES	SUBZONES
UPPER CRETACEOUS	MAESTRICHTIAN	*Baculites baculus*	*HAPLOPHRAGMOIDES EXCAVATA*	
	CAMPANIAN	*Baculites reesidei* *Baculites cuneatus*	*ANOMALINOIDES SP.*	
		Baculites compressus	*HAPLOPHRAGMOIDES FRASERI*	*Praebulimina kickapooensis*
		Exiteloceras jennyi		*Gaudryina bearpawensis*
		Didymoceras stevensoni		*Dorothia* cf. *smokyensis*
			EOEPONIDELLA LINKI	
		Baculites gregoryensis	*GLOMOSPIRA CORONA*	*Quinqueloculina sphaera*
		Baculites asperiformis		*Spiroplectammina sigmoidina*
		Baculites obtusus	*TROCHAMMINA RIBSTONENSIS*	
	SANTONIAN	*Desmoscaphites bassleri*	*GLOBIGERINELLOIDES SP.*	*Heterohelix* cf. *reussi*
		Scaphites vermiformis		*Gavelinella henbesti*
	CONIACIAN	*Scaphites ventricosus* *Inoceramus deformis*	*BULLAPORA LAEVIS*	
		Scaphites preventricosus	*TROCHAMMINA SP.*	
	TURONIAN		*PSEUDOCLAVULINA SP.*	
		Collignoniceras woollgari	*HEDBERGELLA LOETTERLEI*	*Whiteinella aprica*
		Mytiloides labiatus		*Clavihedbergella simplex*
		Watinoceras reesidei	*FLABELLAMMINA GLEDDIEI*	*Haplophragmoides spiritense*
	CENOMANIAN	*Dunveganoceras hagei*		*Ammobaculites pacalis*
		Dunveganoceras albertense *Dunveganoceras* cf. *conditum*	*VERNEUILINOIDES PERPLEXUS*	*Gaudryina irenensis*
		Acanthoceras athabascense		*Ammobaculites gravenori*
		Beattonoceras beattonense	*TEXTULARIA ALCESENSIS*	
LOWER CRETACEOUS	ALBIAN	*Neogastroplites maclearni* *Neogastroplites muelleri* *Neogastroplites cornutus*	*MILIAMMINA MAÑITOBENSIS*	*Haplophragmoides swareni*
				Haplophragmoides postis goodrichi
		Neogastroplites haasi		*Verneuilina canadensis*
		Inoceramus comancheanus	*HAPLOPHRAGMOIDES GIGAS*	
		Paragastroplites liardensis *Gastroplites* cf. *cantianus*	*GAUDRYINA NANUSHUKENSIS*	*Ammobaculites wenonahae*
		Gastroplites canadensis		*Ammobaculites* sp.
		Gastroplites kingi *Arcthoplites macconnelli*		*Haplophragmoides multiplum*
		Arcthoplites irenensis		*Marginulinopsis collinsi* – *Verneuilinoides cummingensis*
				Trochammina mcmurrayensis
		Cleoniceras subbayleyi		*Rectobolivina* sp.

Table 2.1. Biostratigraphic zones. List of foraminiferal zones and subzones and their relations to molluscan indices from Caldwell *et al.* (1978).

al., 1978) . In northwestern Alberta, the *Verneuilinoides perplexus* is divided into the *Ammobaculites gravenori* and the *Gaudryina irenensis* Subzones. The *Ammobaculites gravenori* Subzone extends from the top of the Dunvegan Formation to about 3 meters below the Doe Creek sandstone at its stratotype location in the Doe Creek Canyon (Stelck and Wall, 1955; Caldwell *et al.*, 1978). This interval is interpreted to be the approximate equivalent of the ammonite Subzone *Dunveganoceras* cf. *conditum* of the

Dunveganoceras Zone and the *Acanthoceras athabascense* Zone (Caldwell *et al.*, 1978). The *Gaudryina irenensis* Subzone extends from approximately 3 meters below the Doe Creek Sandstone to the top of the Pouce Coupe Sandstone. This interval approximately spans the molluscan indices of the *Dunveganoceras* cf. *conditum* and *Dunveganoceras albertense* Subzones of the *Dunveganoceras* Zone (Stelck and Wall, 1955; Caldwell *et al.* 1978). The stratigraphically higher Howard Creek Member is characterized by microfossils of the *Flabellammina gleddiei* foraminiferal Zone.Wallace-Dudley and Leckie (1995) undertook a regional sedimentology and source-rock potential study of the Lower Kaskapau Formation in northwest Alberta. To establish the relationship between the Doe Creek Sandstone found in outcrop and those sandstones present in subsurface in Valhalla Field occurring at a similar stratigraphic position, microfaunal analysis was conducted on samples collected from five cores. Samples collected spanned intervals from approximately 12 m below to 15 m above the sandstones of the Doe Creek Member. All samples were found to be of Late Cenomanian age falling within the *Verneuilinoides perplexus* Zone. This zone comprises the lower part of the Kaskapau formation to the base of the Pouce Coupe Member in the Peace River Area.

Wallace-Dudley and Leckie (1995) confirmed the identification of the sandstone in question in Valhalla Field as the Doe Creek Member paleontologically by the recognition of the *Ammobaculites gravenori* and *Gaudryina irenensis* Subzones within the *Verneuilinoides perplexus* Zone. These observations are consistent with those made on the microfaunal assemblages in the Pouce Coupe and Spirit River sections of Stelck and Wall (1955). The diversity of foraminiferal assemblages recovered in the cores of the Doe Creek Member undergo a progressive decline at higher stratigraphic levels. This progression indicates a shoaling trend corresponding to the coarsening-upward trends capped by the Doe Creek Member sandstones (Wallace-Dudley and Leckie, 1995). A return to a more diverse foraminiferal suite is noted in the shales immediately above the sandstone indicating a return to relatively deeper water. All foraminiferal assemblages recovered are considered to represent relatively shallow water such as an inner shelf environment. Arenaceous forms dominate the assemblages recovered, with calcareous forms disappearing closer to the sandstones, indicating both a shoaling trend in water depth and a possible reduction in salinity (Wallace-Dudley and Leckie, 1995).

2.3 Stratigraphic Relationships

The Kaskapau Formation comprises the lowest portion of the Smoky Group consisting predominantly of dark grey, marine shales and mudstones in the foothills and Peace River Plains (Figure 2.5). The Kaskapau Formation displays a pronounced wedge-shaped geometry, thinning from greater than 500 m in the western parts of the basin (Stott, 1967), to less than 50 m thick to the east (Plint, 2000). The Kaskapau Formation overlies the Dunvegan Formation and is overlain by Turonian Cardium Formation; both contacts are considered conformable (Gleddie, 1949; Stott, 1967). The contact between the Kaskapau Formation and Dunvegan Formation displays an inter-fingering, retrogradational relationship (Stott, 1982; Bhattacharya and Walker, 1991a; Plint 2000). This contact is diachronous causing the contact between the Dunvegan and Kaskapau Formations to be placed at stratigraphically higher intervals as the Kaskapau mudstones

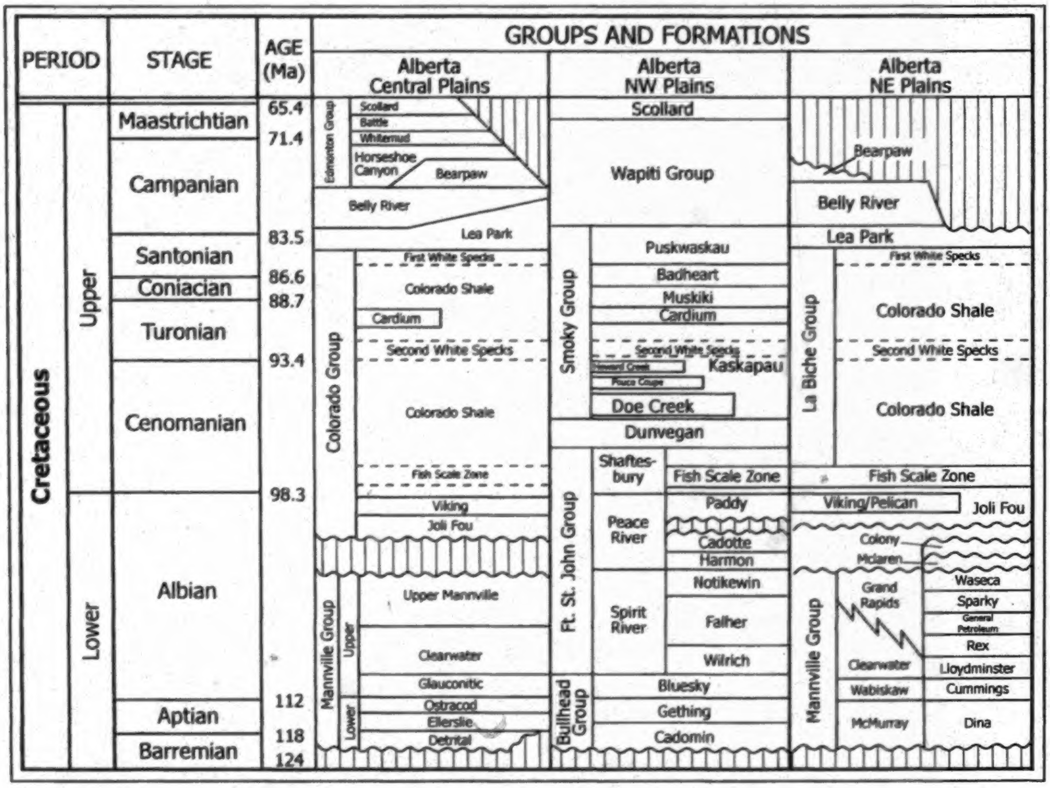

PERIOD
STAGE
AGE (Ma)
GROUPS AND FORMATIONS
Alberta Central Plains
Alberta NW Plains
Alberta NE Plains
Cretaceous
Upper
Lower
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
65.4
71.4
83.5
86.6
88.7
93.4
98.3
112
118
124
Edmonton Group
Scollard
Battle
Whitemud
Horseshoe Canyon
Bearpaw
Belly River
Lea Park
Colorado Group
First White Specks
Colorado Shale
Cardium
Second White Specks
Colorado Shale
Fish Scale Zone
Viking
Joli Fou
Mannville Group
Upper
Lower
Upper Mannville
Clearwater
Glauconitic
Ostracod
Ellerslie
Detrital
Scollard
Wapiti Group
Smoky Group
Puskwaskau
Badheart
Muskiki
Cardium
Second White Specks
Howard Creek
Pouce Coupe
Kaskapau
Doe Creek
Dunvegan
Ft. St. John Group
Shaftesbury
Fish Scale Zone
Peace River
Paddy
Cadotte
Harmon
Spirit River
Notikewin
Falher
Wilrich
Bullhead Group
Bluesky
Gething
Cadomin
Bearpaw
Belly River
Lea Park
La Biche Group
First White Specks
Colorado Shale
Second White Specks
Colorado Shale
Fish Scale Zone
Viking/Pelican
Joli Fou
Colony
Mclaren
Waseca
Sparky
General Petroleum
Rex
Lloydminster
Cummings
Dina
Mannville Group
Grand Rapids
Clearwater
Wabiskaw
McMurray

Figure 2.5. Stratigraphic chart of Cretaceous strata in the Western Candian Sedimentary Basin (modified from Pemberton and MacEachern, 1995).

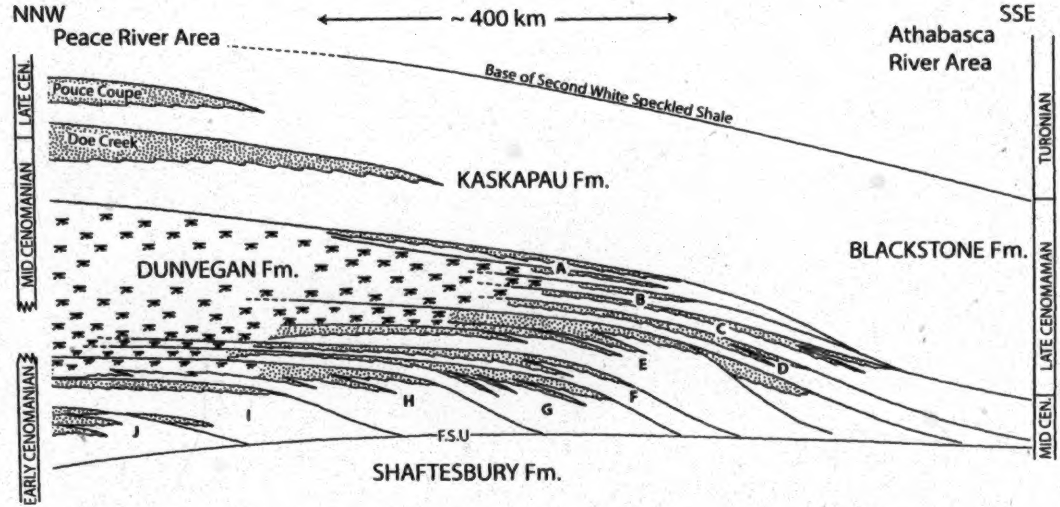

NNW
~ 400 km
SSE
Peace River Area
Athabasca River Area
Base of Second White Speckled Shale
LATE CEN.
MID CENOMANIAN
EARLY CENOMANIAN
TURONIAN
LATE CENOMANIAN
MID CEN.
Pouce Coupe
Doe Creek
KASKAPAU Fm.
BLACKSTONE Fm.
DUNVEGAN Fm.
A
B
C
D
E
F
G
H
I
J
F.S.U
SHAFTESBURY Fm.

Figure 2.6. Dunvegan and Kaskapau stratigrapy. Schematic cross section from north northwest to south southeast illustrating the relationship between the Shaftesbury, Dunvegan, and Kaskapau Formation (modified from Plint, 2000).

backstep to the northwest, illustrated in figure 2.6 (Stelck and Wall, 1955; Stelck *et al.* 1958; Stott, 1967; Singh, 1983).

Stelck and Wall (1954) divided the Kaskapau Formation into “Lower”, “Middle”, and “Upper” units. The Lower unit comprises deposits from the top of the Dunvegan Formation to the top of the Pouce Coupe Sandstone, the Middle unit comprises deposits from the top of the Pouce Coupe Sandstone to the top of the Second White Speckled Shale (SWSS), and the Upper unit comprises deposits from the top of the SWSS to the base of the Cardium Formation. The Second White Speckled Shale is a well known, yet informal, shale package characterized by white calcareous specks composed of aggregates of microfossils which is correlative with the Middle Kaskapau Formation and marks the Cenomanian-Turonian boundary (Stelck and Wall, 1954; Singh, 1983; Wallace-Dudley and Leckie, 1993). The Second White Speckled shale occurs approximately 11.6 m above the Howard Creek Member where it outcrops along Howard Creek (Wallace-Dudley and Leckie, 1993) and manifests as a high gamma ray marker horizon on well logs in the study area. Based on work done in northeastern British Columbia, Stott (1967) divided the Kaskapau into four Members (Sunkay, Vimy, Haven, and Opabin in ascending order) based on the content of calcite or siderite and the presence or absence of concretions. In the Peace River Plains, the Sunkay Member is correlative with the lower part of the Kaskapau comprising the Doe Creek, Pouce Coupe, and Howard Creek Members.

Detailed allostratigraphic studies by Plint (2000, 2001) and Kreitner (2001) demonstrated the Lower Kaskapau Formation comprises twenty-one coarsening-upward sequences. These sequences were then divided into two intervals; 1) the basal Kaskapau comprising those units above the Dunvegan "A" allomember and "X" surface, and 2) the Lower Kaskapau between the "X" and "K1" surface. The "X" surface is a regionally extensive, robust flooding surface. Plint *et al.*, (1993) proposed a major beveling unconformity, termed the "K1" unconformity, separated the Pouce Coupe and Doe Creek Sandstones from younger Kaskapau strata. This interpretation was based on regional stratigraphic evaluation whereby the "K1" surface appears to truncate underlying markers of the Pouce Coupe and Doe Creek Members as well as apparent onlap of younger Kaskapau markers onto the "K1" surface. Figure 2.7 illustrates three type well logs of the Doe Creek Member within the study area. The top of the Dunvegan Formation, the "X" marker and "K1" surface of Plint (2000), and the "DCM1" surface, the datum utilized in this study is annotated. The interval of interest is those strata found between the "X" and "K1" surfaces.

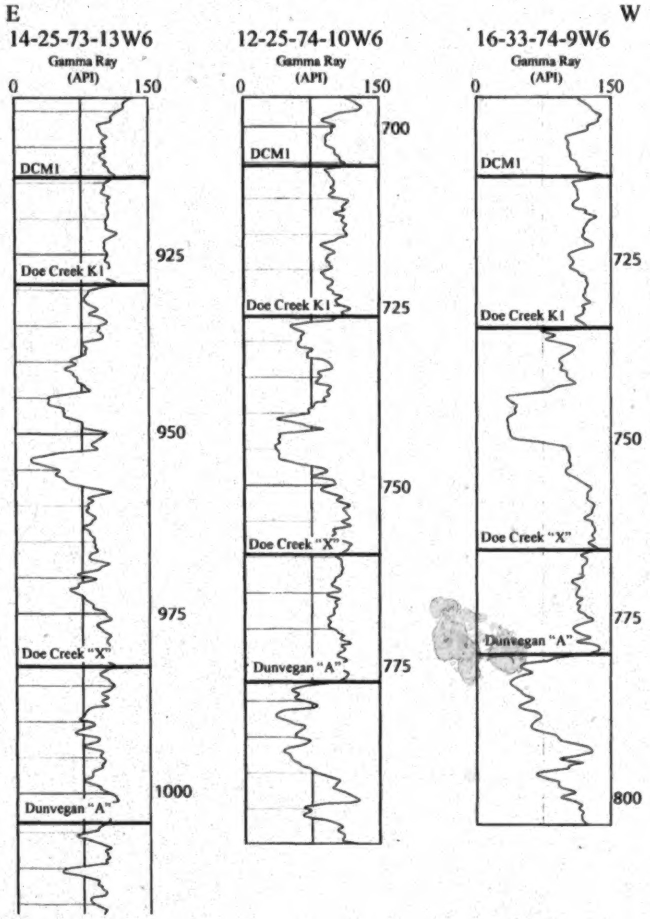


Figure 2.7. Type well logs of the Doe Creek Member within the study area.

2.4 PALEOGEOGRAPHY

During the Cretaceous, the Western Interior of North America was subject to complex interactions between the aforementioned tectonic activity related to the formation of the foreland basin and changes in global eustatic sea level. The Western Interior was flooded during the early Cretaceous both from cratonward incursions from the circum-boreal seaway, and the ancient Gulf of Mexico. The two embayments were first joined in a continuous seaway in the early-late Albian time. In late-late Albian time, the seas experienced a partial retreat, forming two distinct embayments, but were joined again in latest Albian-Early Cenomanian time (Williams and Stelck, 1975). Figure 2.8 shows the approximate extent of the Western Interior Seaway during the Late Cenomanian at the time of deposition of the Doe Creek Member. The epeiric Western Interior Seaway remained continuous from between the Gulf of Mexico and the Boreal Sea for approximately 35 Ma (Kauffman, 1984).

The paleogeographic and stratigraphic evolution of the Western Interior Seaway was controlled largely by tectonic activity in the foreland basin and eustatic sea-level fluctuation. The Dunvegan Formation conformably underlies the Kaskapau Formation and was deposited as a major regressive unit corresponding to the second major episode

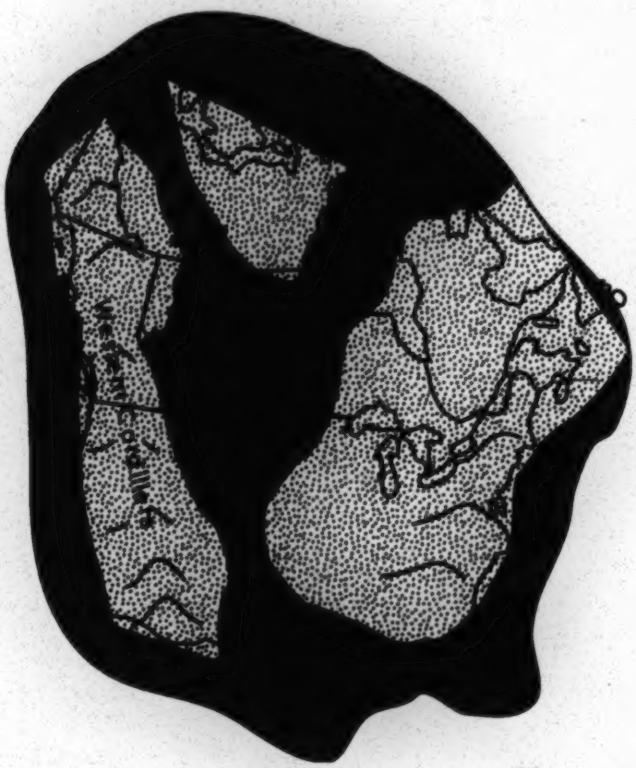


Figure 2.8. Paleogeographic recontruction. The approximate extent of the Western Interior Seaway of North America during the late Cenomanian (modified from Bhattacharya, 1993).

of the Columbian Orogeny (Stott, 1984). The Dunvegan Formation is characterized by marine sandstones and mudstones of predominantly deltaic origin in west-central Alberta, and transitions to alluvial conglomerates to the northeast (Figure 2.9). Haq *et al*. (1987) presented global third-order sea-level charts for the Cretaceous, indicating a major eustatic drop in the mid-Cenomanian (approximately 94 Ma) that is likely correlative with the major regression noted in the Dunvegan (Bhattacharya, 1989). The top of the Dunvegan Formation is a major flooding surface related to a major eustatic rise in sea-level termed the Greenhorn Transgression (Kauffman, 1984). The Kaskapau Formation was deposited during this global sea-level rise culminating in the deposition of the Second White Speckled shale during peak transgression. The Doe Creek Member represents deposition during minor regressive events during this overall transgression, and likely exhibited a similar paleogeography to that of the upper allomembers of the Dunvegan Formation (*cf.* Bhattacharya and Walker, 1991b; Plint, 2000). The Dunvegan Formation is sourced from the Omineca intrusion to the northwest, as evidenced by the arkosic nature of the lower parts of the Dunvegan (Stelck *et al.* 2002). The source of the Doe Creek sandstones are interpreted to be the isostatically-uplifted Dunvegan sediments of the Hay River and Keg River subbasins (Stelck *et al.* 2002)

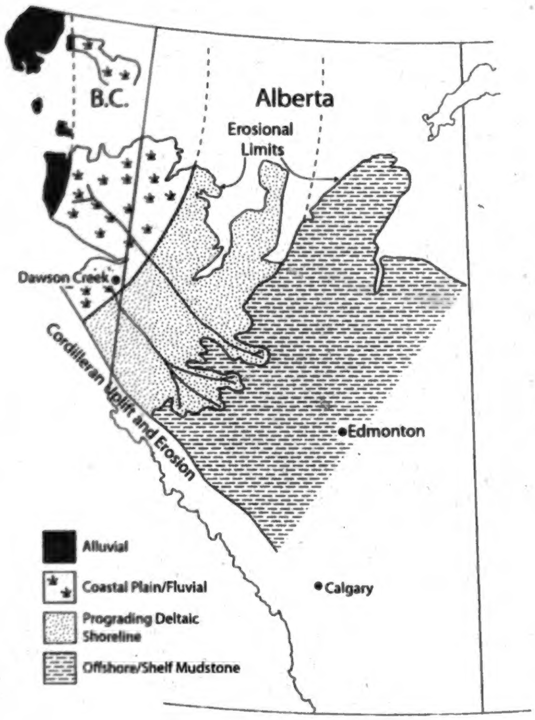

B.C.
Alberta
Erosional Limits
Dawson Creek
Cordilleran Uplift and Erosion
Edmonton
Calgary
Alluvial
Coastal Plain/Fluvial
Prograding Deltaic Shoreline
Offshore/Shelf Mudstone

Figure 2.9. Dunvegan Formation paleogeography. (modifed from Leckie and Smith, 1992).

2.5 PREVIOUS WORK

Dawson (1881), as one of the pioneering geologists to explore northwestern Alberta and northeastern British Columbia, named the shales exposed along the Smoky River the Smoky River Formation. McLearn (1919) subdivided the Smoky River Formation into a lower shale unit, a middle (Badheart) sandstone, and an upper shale unit and assigned the name Kaskapau to the lower shale (McLearn, 1926). The Smoky River Formation was raised to group status by McLearn and Henderson (1944) and the name later shortened to Smoky Group, comprising the Kaskapau, Bad Heart, and Puskwaskau formations. Warren and Stelck (1940) named a sandstone lying below the Pouce Coupe Sandstone and above the base of the Kaskapau Formation the Doe Creek Sandstone. Stelck and Wall (1954, 1955) described the foraminiferal zones in the Peace River area, dividing the Kaskapau into three units: "Lower" (including the Doe Creek and Pouce Coupe sandstones), "Middle" (including the Howard Creek sandstone and the Second White Speckled Shales), and "Upper" (the sediments between the Second White Speckled Shales and the Cardium Sandstones) Kaskapau. A lithostratigraphic re-examination of the Smoky Group was undertaken by Stott (1963, 1967) who subdivided the Kaskapau Formation into the Sunkay, Vimy, Haven, and Opabin Members based on lithological characteristics. The Doe Creek Member lies within the Lower Kaskapau of Stelck and Wall (1954, 1955) and the Sunkay Member of Stott (1963, 1967)

The discovery of Doe Creek oil pools in Valhalla Field, Alberta, sparked new interest in the Lower Kaskapau Formation in the late 1970's and early 1980's (Dearborn, 1984; Dearborn *et al.*, 1985). Local, subsurface studies of the Doe Creek Member within Valhalla Field were undertaken focusing on sedimentology, regional stratigraphy, source rock potential of the surrounding shales, reservoir properties, and exploitation techniques (Wallace-Dudley and Leckie, 1988, 1993, 1995; Hogg *et al.*, 1998). Regional allostratigraphic studies have been undertaken with aims to establish a regional, high-resolution stratigraphic framework for the Dunvegan and Kaskapau Formations (Bhattacharya and Walker, 1991a; Plint *et al.*, 1993; Plint 2000). The influence of basement tectonics on Cretaceous sedimentation in the Peace River Arch region of Alberta was examined by Stelck (1975), Plint *et al.* (1993), Chen and Bergman (1999). More recently, non-marine strata, equivalent to the marginal- and shallow-marine deposits of the Doe Creek Member at Valhalla Field, have been discovered and documented in the Dunvegan area of the Peace River (Kreitner, 2001; Plint, 2001)

CHAPTER THREE

FACIES ANALYSIS AND FACIES ASSOCIATIONS

3.1 INTRODUCTION

Eleven facies have been defined in the Doe Creek Member, based on detailed analysis of lithology, primary sedimentary structures, and ichnology. The terminology used herein to describe the depositional zonation of shoreline profiles follows the usage of MacEachern and Pemberton (1992), Pemberton and MacEachern (1995; 1997), and Pemberton *et al.* (2001). This classification scheme is based on recurring ichnofacies and sedimentary structures, and is summarized in Table 3.1.

Fifty-five cored intervals from the Doe Creek Member, totaling approximately 930 meters in length, were analyzed sedimentologically and ichnologically (locations shown in Figure 1.1). The ichnological analysis included identification of ichnogenera, relative abundance of total trace fossil occurrence (bioturbation intensity), trace fossil size, cross-cutting relationships, and diversity of the ichnological suites. Sedimentological analysis focused on features such as lithology, grain-size, primary sedimentary structures, bedding contacts and styles, bed thickness, and penecontemporaneous deformation structures. Grain size was determined using a Can-Strat grain size card. Comparison between Can-Strat grain size terminologies with standard units of measurement are given in Table 3.2. Trace fossil genera presented herein are followed by abbreviations, according to their relative abundance: very rare (vr); rare (r); moderate (m); common (c); and abundant (a).

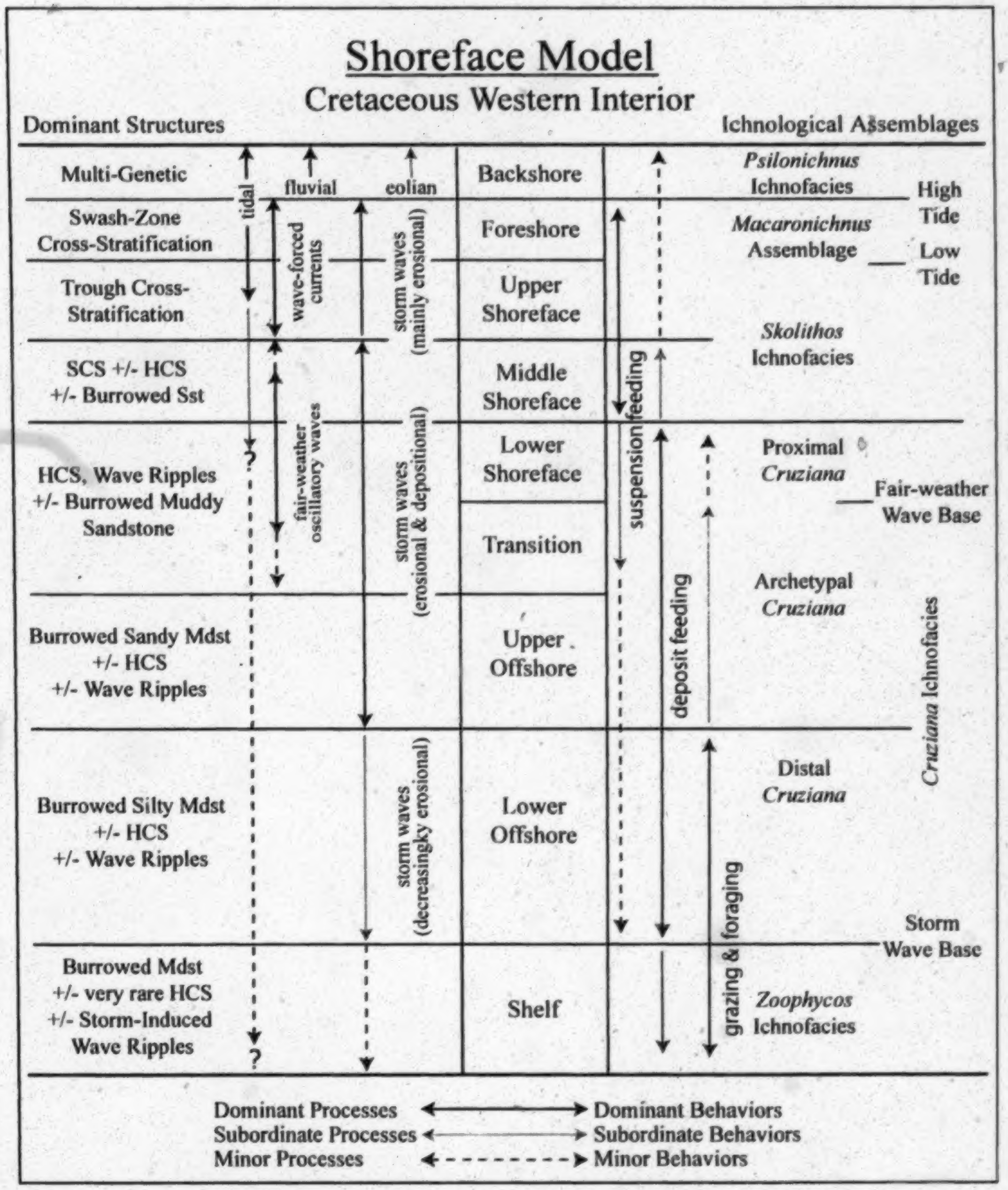

Shoreface Model
Cretaceous Western Interior
Dominant Structures
Ichnological Assemblages
Multi-Genetic
tidal
fluvial
eolian
Backshore
Psilonichnus
Ichnofacies
High
Tide
Swash-Zone
Cross-Stratification
wave-forced
currents
storm waves
(mainly erosional)
Foreshore
Macaronichnus
Assemblage
Low
Tide
Trough Cross-
Stratification
Upper
Shoreface
Skolithos
Ichnofacies
SCS +/- HCS
+/- Burrowed Sst
Middle
Shoreface
suspension feeding
HCS, Wave Ripples
+/- Burrowed Muddy
Sandstone
?
fair-weather
oscillatory waves
storm waves
(erosional & depositional)
Lower
Shoreface
Proximal
Cruziana
Fair-weather
Wave Base
Transition
Archetypal
Cruziana
Burrowed Sandy Mdst
+/- HCS
+/- Wave Ripples
Upper
Offshore
deposit feeding
Cruziana Ichnofacies
Burrowed Silty Mdst
+/- HCS
+/- Wave Ripples
storm waves
(decreasingky erosional)
Lower
Offshore
Distal
Cruziana
grazing & foraging
Storm
Wave Base
Burrowed Mdst
+/- very rare HCS
+/- Storm-Induced
Wave Ripples
?
Shelf
Zoophycos
Ichnofacies
Dominant Processes
Dominant Behaviors
Subordinate Processes
Subordinate Behaviors
Minor Processes
Minor Behaviors

Table 3.1. Idealized ichnological and sedimentological shoreface model based on observations in the Cretaceous Western Interior of North America (modified from MacEachern et al., 1999a).

Can-Strat Terminology	Diameter (µm)	Phi (ø) size
Very coarse sand		
vcU	1410-2000	-0.5 to -1.0
vcL	1000-1410	0.0 to -0.5
Coarse sand		
cU	710-1000	0.5 to 0.0
cL	500-710	1.0 to 0.5
Medium sand		
mU	350-500	1.5 to 1.0
mL	250-350	2.0 to 1.5
Fine sand		
fU	177-250	2.5 to 2.0
fL	125-177	3.0 to 2.5
Very fine sand		
vfU	88-125	3.5 to 3.0
vfL	62.5-88	4.0 to 3.5
Silt	3.9-62.5	8.0 to 4.0
Clay	0.06-3.9	14.0 to 8.0
* U=upper; L=lower		

Table 3.3. Grain size table utilized in the facies analysis of this study

3.2 FACIES DESCRIPTION AND INTERPRETATION

3.2.1 Facies 1A: Dark grey to black claystones and mudstones

Lithology and Sedimentary Features:

Facies 1A comprises well-indurated, laminated to massive, dark grey claystones, mudstones, and shales (Figure 3.1). Lower very fine-grained sand and silt occur in rare, lenticular beds that make up approximately five percent of the facies by volume. These sandy beds exhibit normal grading, are on the scale of 0.5 to 3 cm centimeters thick, and display low-angle wavy parallel lamination and sediment-starved, combined-flow ripple cross-lamination (Figure 3.1.B). These siltstone and sandstone beds locally exhibit moderate degrees of soft-sediment deformation and loading structures at their bases. Thin zones (typically less than 10 cm in thickness) of this facies exhibit siderite mineralization. Other sedimentary features present in Facies 1A include disseminated fish scales, siderite nodules, septarian concretions, plant fragments that may be pyritized or coalified, and finely comminuted carbonaceous detritus. Diminutive, disarticulated, intact shells such as *Lingula* sp. (Figure 3.1.C) can be found on bedding planes within Facies 1A.

Ichnology:

The intensity of visible bioturbation is generally low to moderate. Ichnogenera present include *Helminthopsis* (r-m), *Phycosiphon* (r-m), *Chondrites* (r-m), thin-walled *Schaubcylindrichnus freyi* (r), *Zoophycos* (r) and *Planolites* (r). The thin sandstone and siltstone beds locally display rare instances of fugichnia. Epichnial and hypichnial features are observed on bedding planes, possibly representing casts of surface grazing traces.

Interpretation:

Facies 1A is interpreted to have been deposited under conditions of slow, continuous sedimentation in relatively deep, quiescent open marine water. This is consistent with marine shelf conditions where deposition is predominantly via suspension fallout. The siltstone and sandstone beds exhibit sedimentary structures consistent with rapid emplacement by storm-generated oscillatory currents and are therefore interpreted as distal tempestites. The deformation associated with these tempestite beds and the load-casted bases stem from the soft to soupy character of the subjacent fine-grained substrate.

The low bioturbation intensities observed could be caused by unfavorable

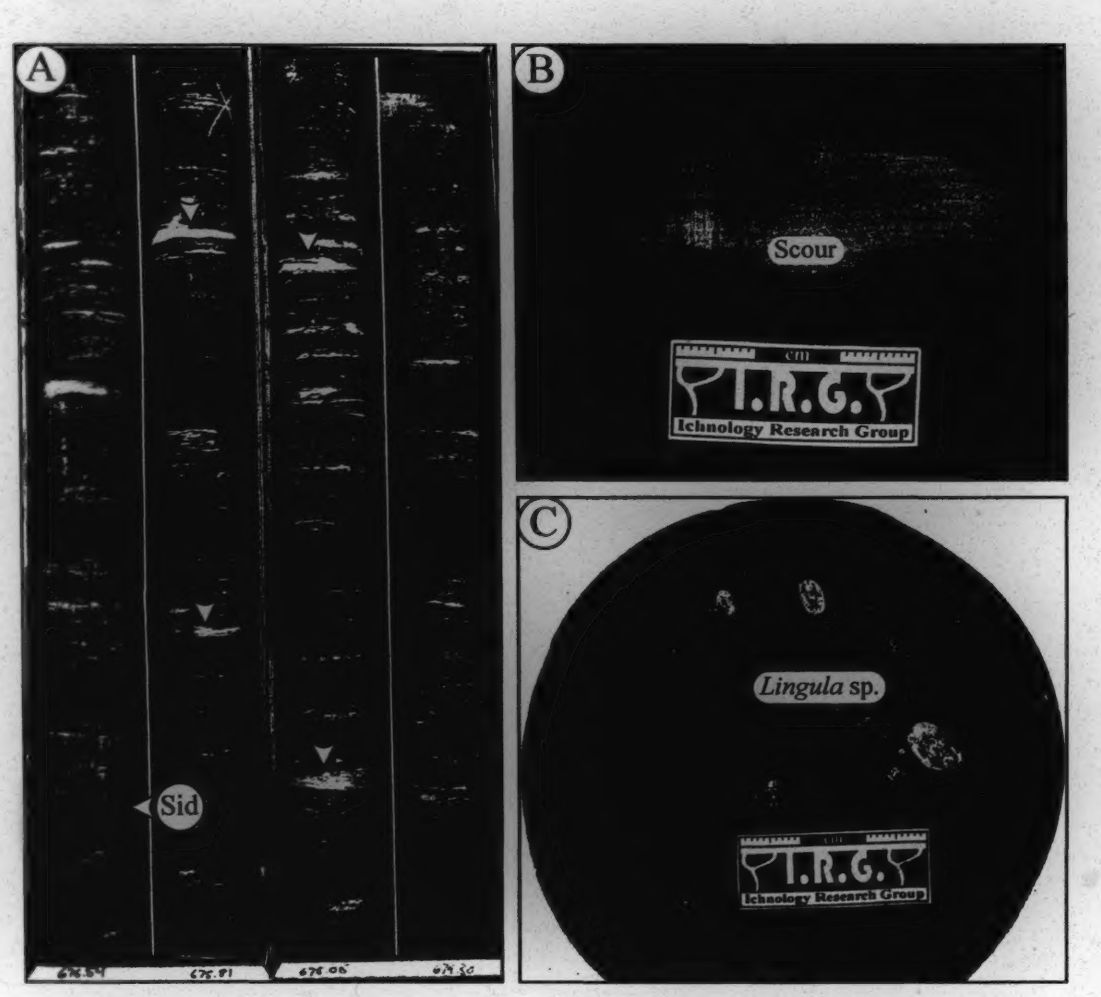
Figure 3.1. Facies 1A: Dark grey to black claystones and mudstones.

Shelf

A) Typical appearance of Facies 1A. Thin (<2cm), light colored sandstone and siltstone beds (demarcated by white arrows) are visible and represent the distal expression of storm-induced tempestites and turbidites. A large siderite nodule (sid) is visible in the lower left corner. Core boxes are approximately 75cm long; bottom is lower left, top is upper right. Well 07-25-75-10W6, boxes 1 and 2 of 13; depth 676.54m to 673.6m.

B) Close up view of a storm bed in Facies 1A. Note the scoured base, normally graded bedding, and combined-flow ripple cross-lamination. The combined-flow ripple cross-lamination indicates a moderate level of wave influence suggesting either a large storm event occurred, causing wave orbital motion to impinge on the shelf or this sample is near the transition to the lower offshore. Well 06-25-75-10W6, depth 715.3m.

C) Close up of a bedding plane view in Facies 1A. Small disarticulated *Lingula* sp., lying parallel to bedding indicate transport occurred post-mortem. The transport mechanism is inferred to be a storm event. Well 11-09-75-9W6, depth 720.3m.


A
B
C
Scour
Sid
Lingula sp.
cm
I.R.G.
Ichnology Research Group
675.54
675.81
676.05
676.30

conditions such as dysaerobia or cool temperatures that can be found in deep shelf settings, or due to lack of lithologic contrast between bioturbation structures and host substrate. Another probable explanation of the apparent lack of visible bioturbation is the soupy nature of fine-grained substrates. The ichnological assemblages of fine-grained substrates in deep, quiescent-water conditions are typically dominated by horizontal grazing and foraging structures (Seilacher, 1967; Ekdale *et al.*, 1984; Pemberton *et al.*, 1992a; Pemberton *et al.*, 2001). However, these types of trace fossils have poor preservational potential due to the large amount of dewatering and compaction fine-grained substrates undergo during lithification (*cf.* MacEachern *et al.*, 1992; MacEachern *et al.*, 1999a). Based on discernible bioturbation, the ichnological assemblage is consistent with that of the *Zoophycos* ichnofacies or a distal expression of the *Cruziana* ichnofacies (Pemberton and MacEachern, 1995, MacEachern *et al.*, 1999a; Pemberton *et al.*, 2001).

3.2.2 Facies 1B: Moderately bioturbated silty mudstone

Lithology and Sedimentary Features:

Facies 1B comprises massive, pervasively bioturbated, dark grey to black mudstone with dispersed silt (10-30% by volume) and rare, isolated lower very fine-grained sandstone beds (Figure 3.2.). These sandstone beds are typically 0.5 to 6 cm in thickness. The bioturbation intensities of the mudstones typically range from sixty to ninety percent, leading to the destruction of most primary sedimentary structures. The isolated sandstone beds are relatively unbioturbated showing low to moderate bioturbation intensities, with intensities increasing from the base to the top of each bed (Figures 3.2.A, 3.2.B, and 3.2.C). Sedimentary structures in these horizons include normally graded bedding, low-angle undulatory parallel lamination, combined-flow ripple cross-lamination and less common oscillatory ripple cross-lamination. Facies 1B typically overlies Facies 1A gradationally, and the two are commonly intercalated.

Ichnology:

Bioturbation intensities in the silty mudstones of Facies 1B are moderate to pervasive, imparting a massive or churned appearance. Ichnogenera are typically uniformly distributed and include *Helminthopsis* (m), *Zoophycos* (m), *Schaubcylindrichnus* (m), *Phycosiphon* (m), *Planolites* (r-m), *Chondrites* (r-m), with less common *Thalassinoides* (vr). Within the sandstone beds, a suite comprising *Teichichnus* (vr), *Rhizocorallium* (vr), *Siphonichnus* (vr), and *Palaeophycus* (vr) dominates (Figs.

Figure 3.2. Facies 1B: Moderately bioturbated silty mudstone.

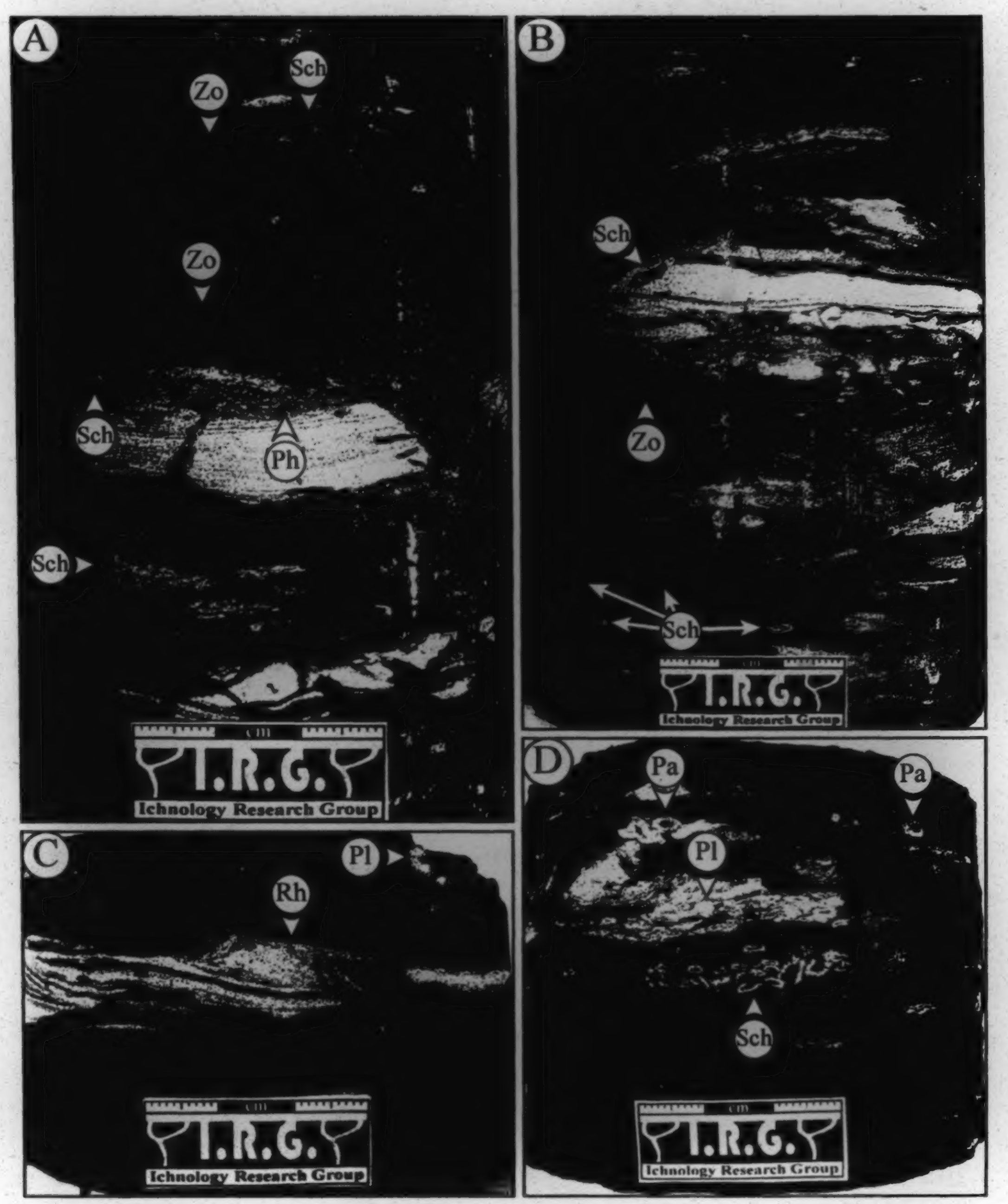
Distal Lower Offshore

A) Typical appearance of Facies 1B. The irregularity of the sandstone and siltstone beds is due to biogenic modification. Note the abundant *Phycosiphon* (Ph) in the upper portion of the conspicuous, light colored sandstone bed. *Schaubcylindrichnus freyi* (Sch) and *Zoophycos* (Zo) are also visible. The mudstones comprise higher silt content than Facies 1A and are typically poorly sorted due to bioturbation. Well 14-31-74-10W6, depth 748.9m.

B) The light colored, agglutinated silt and sand walls of *Schaubcylindrichnus freyi* (Sch) are clearly visible against the highly bioturbated, dark colored background containing abundant *Zoophycos* (Zo). Well 16-35-75-11W6, depth 710.6m

C) Close up view of a distal storm bed displaying a scoured base and parallel lamination. Note the gently inclined *Rhizocorallium* (Rh) cutting across the storm bed, destroying primary lamination. Several *Planolites* (Pl) are visible in the upper right portion of the picture. Well 16-35-75-11W6, depth 709.73m

D) Note the complete destruction of primary sedimentary fabric in the sandstone lens. Discernible ichnogenera present include *Schaubcylindrichnus* (Sch), *Planolites* (Pl), and *?Palaeophycus* (Pa). Well 08-34-74-12W6, depth 803.9m.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3.2.C and 3.2.D).

Interpretation and Discussion:

Facies 1B is interpreted to represent deposition in the distal lower offshore within the influence of maximum (storm) wave base. The low-angle wavy parallel cross-lamination associated with the siltstone and sandstone beds are interpreted as hummocky cross-stratification, while the combined-flow ripple cross-lamination likely represents the waning stage of storm wave energy. These beds are therefore interpreted to represent distal tempestites. The tempestites occur more frequently and are commonly thicker in Facies 1B than those of Facies 1A. The moderately diverse trace fossil assemblage dominated by grazing/foraging and deposit feeding strategies coupled with high bioturbation intensities are interpreted to reflect a distal expression of the *Cruziana* ichnofacies, indicative of well-oxygenated, open-marine environments (Pemberton and MacEachern 1995, MacEachern *et al.* 1999a; Pemberton *et al.* 2001). The ancillary ichnological elements associated with the tempestites are inferred to represent opportunistic colonization of the storm-emplaced sandstone beds (Pemberton and Frey, 1984; Seilacher and Aigner, 1991; Pemberton *et al.*, 1992b; Pemberton and MacEachern 1997). The increased abundance and average thickness of these tempestites, coupled with a higher amount of silt- and sand-sized clasts within the fair-weather mudstones, indicate a slightly more proximal setting than interpreted for Facies 1A. Facies 1B is therefore inferred to represent deposition in a proximal shelf to distal lower offshore setting, subject to periodic storm wave activity.

3.2.3 Facies 2: Pervasively bioturbated sandy mudstone and siltstone

Lithology and Sedimentary Features:

Facies 2 is characterized by pervasively bioturbated sandy mudstone and sandy siltstone (Figures 3.3 and 3.4). This facies commonly cleans and coarsens upward as the mud content decreases from 70-80% to approximately 30% by volume and upper fine-grained sand grains appear. Bioturbation is intense, and thus primary sedimentary structures are very rare or absent. The bioturbation also serves to disperse the silt- and sand-sized grains throughout the mudstones, resulting in a predominantly homogeneous texture. Rare 1-8 cm thick sandstone beds occur intercalated with the mudstones and siltstones, and show an upward increase in bioturbation (Figures 3.4.A, 3.4.B, and 3.4.C). These sand-rich beds are normally graded and display low-angle wavy parallel cross-lamination and less common combined-flow ripple cross-lamination and oscillation ripple

Figure 3.3. Facies 2:Pervasively bioturbated sandy mudstone/sandy siltstone.

Lower Offshore

A) Note that the prominent *Zoophycos* (Zo) burrow displays sand-enrichment in the backfill structure. Well 08-23-71-8W6, depth 1053.35m.

B-D) Typical appearance of Facies 2 in the Doe Creek Member. *Zoophycos* (Zo), *Phycosiphon* (Ph), *Helminthopsis* (He), *Planolites* (Pl), *Palaeophycus* (Pa), ?*Thalassinoides* (Th), *Schaubcylindrichnus freyi* (Sch), *Asterosoma* (As) and *Teichichnus* (Te). **B)** Well 14-25-73-13W6, depth 943.65m. **C)** Well 14-25-73-13W6, depth 945.45m. **D)** Well 14-25-73-13W6, depth 944.15m.

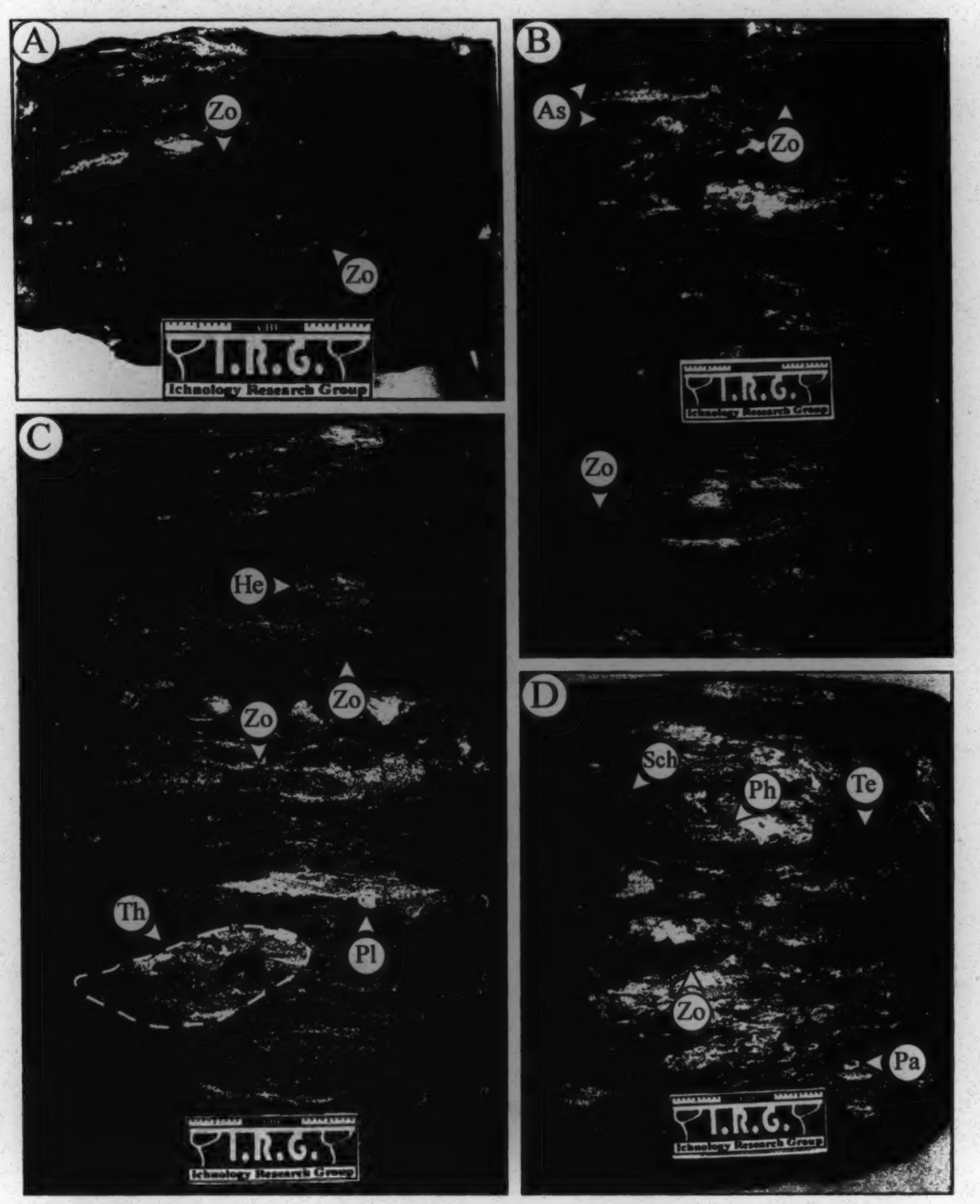
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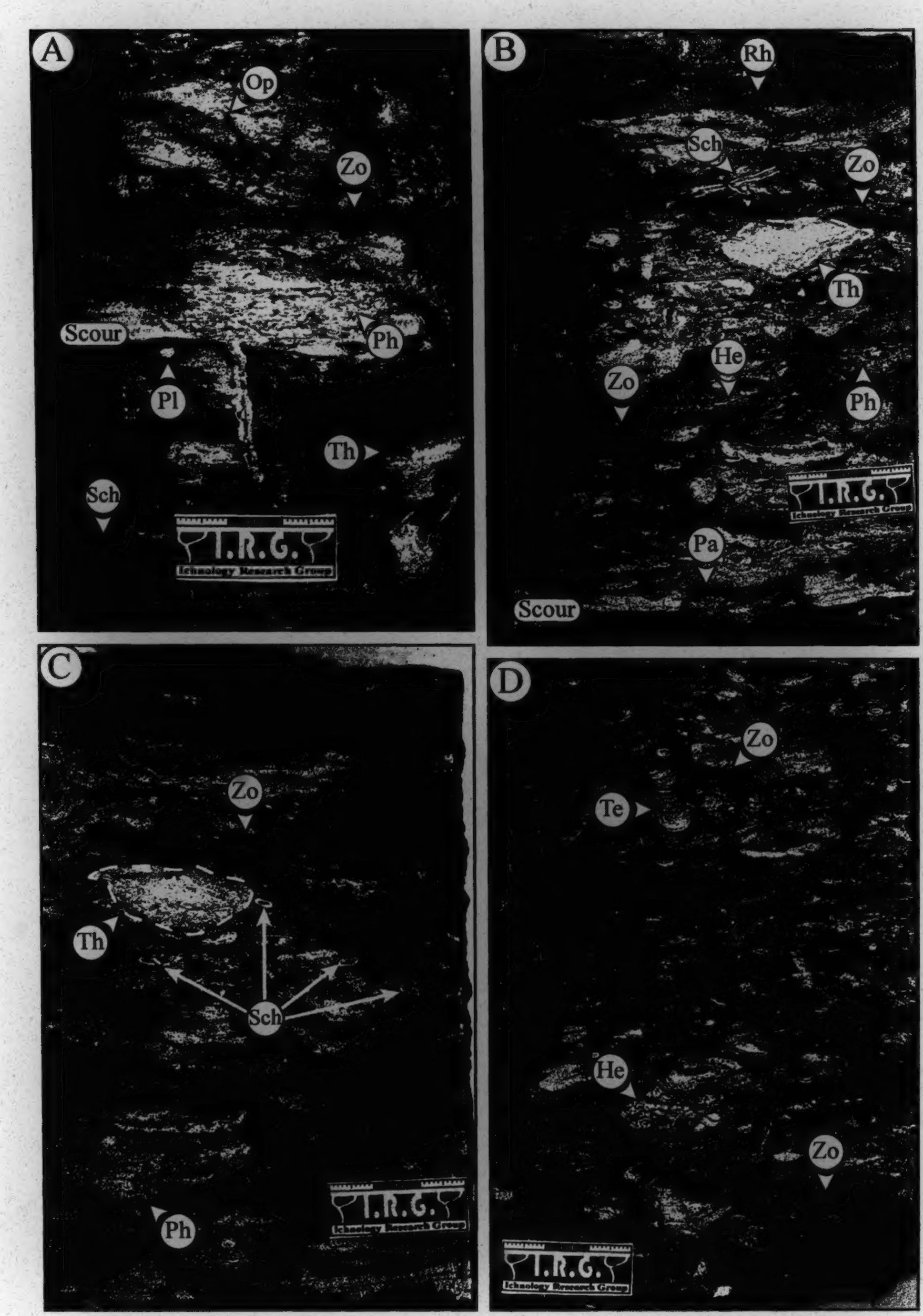
Figure 3.4. Facies 2: Pervasively bioturbated sandy mudstone/sandy siltstone.

Lower Offshore

A) and B) Typical appearance of relatively large (>5cm) tempestites in Facies 2. Note the erosive scour demarcating the base of sand-rich bed. Some wavy parallel lamination is still visible in figure 2.4.B. The tempestites have been almost completely bioturbated leading to sand-rich horizons in an otherwise mud and silt dominated unit. Trace fossils present include *Zoophycos* (Zo), *Phycosiphon* (Ph), *Rhizocorallium* (Rh), *Helminthopsis* (He), *Planolites* (Pl), *Palaeophycus* (Pa), *Schaubcylindrichnus freyi* (Sch), *Thalassinoides* (Th), and ?*Ophiomorpha* (Op). A) Well 14-25-73-13W6, depth 944.95m. B) Well 13-13-73-13W6, depth 986.5m.

C) and D) Trace fossils of Facies 2. *Zoophycos* (Zo), *Phycosiphon* (Ph), *Rhizocorallium* (Rh), *Planolites* (Pl), *Helminthopsis* (He), *Palaeophycus* (Pa), *Schaubcylindrichnus freyi* (Sch), *Thalassinoides* (Th), *Teichichnus* (Te). C) Well 13-13-73-13W6, depth 986.8m. D) Well 08-09-73-12W6, depth 1012.4m.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cross-lamination.

Ichnology:

Facies 2 displays very high bioturbation intensities and ichnogenera diversity (Figures 3.3 and 3.4). Positive identification of individual traces can be difficult, due to overprinting and cross-cutting relationships. Trace fossils are uniformly distributed throughout Facies 2. The dominant elements of the trace fossil suite are *Helminthopsis* (m), *Zoophycos* (m-c), *Phycosiphon* (m-c), *Planolites* (m), *Schaubcylindrichnus freyi* (m-c), *and Chondrites* (m-c) with ancillary elements including *Teichichnus* (r), *Scolicia* (vr), *Thalassinoides* (r), and *Rhizocorallium* (r-m). *Asterosoma* (vr), *Siphonichnus* (r), *Palaeophycus* (r-m), *Ophiomorpha* (vr), *Skolithos* (vr), and *Diplocraterion* (vr) occur rarely and are found only in association with the moderately bioturbated sandstone beds.

Interpretation and Discussion:

The thorough bioturbation by a diverse suite of ichnogenera in a predominantly fine-grained substrate is consistent with deposition in a well-oxygenated, fully-marine offshore setting. The rare sandstone beds displaying low-angle, wavy parallel lamination and combined-flow ripple cross-lamination are interpreted to be tempestites. The preservational potential of these beds is high due to their emplacement beyond fair-weather wave base where physical processes are typically not capable of reworking them (Dott, 1988; Wheatcroft, 1990, Pemberton *et al.*, 1992b; Pemberton and MacEachern 1997). The potential preservation of the tempestites is further enhanced by the preponderance of small burrow types that display little vertical penetration in the offshore (Pemberton *et al.*, 2001; Bann and Fielding, 2004). The tempestites in Facies 2 are thicker and are more common than those in Facies 1B. Within Facies 2, the tempestites display a upwards-thickening trend and a corresponding increase in prevalence. The increased thickness and incidence of tempestite beds is interpreted to reflect a shoaling trend, although it is possible that the trends seen could result from climatic variation.

The diverse assemblage of deposit-feeding and grazing/foraging behaviors seen in Facies 2 is typical of a distal expression *Cruziana* ichnofacies, and is typical of open-marine, lower offshore deposition.

3.2.4 Facies 3: Pervasively bioturbated muddy sandstone and silty sandstone

Lithology and Sedimentary Features:

Facies 3 is an intensely bioturbated, poorly sorted, silty sandstone that gradationally overlies Facies 2. This facies commonly displays a coarsening- and cleaning-upwards character, manifesting as a decrease in the ratio of mud- and silt-sized grains to sand-sized grains, as well as a shift from lower very fine-grained sand near the base to upper very fine-grained sand at the top. Bioturbation in this facies is pervasive, leading to destruction of most primary sedimentary structures (Figures 3.5 and 3.6). Rare 5-15 cm thick sandstone beds occur, displaying scoured bases and remnant low-angle wavy parallel lamination commonly grading into combined-flow ripple and oscillation ripple cross-lamination. These sandstone beds characteristically display an upward increase in bioturbation, causing a laminated to burrowed texture (*i.e.* lam-scram texture).

Ichnology:

This facies displays very high bioturbation intensities and high ichnogenera diversities and comprises the most diverse ichnological assemblage observed in the Doe Creek Member. The trace fossil suite includes *Zoophycos* (c-a), *Helminthopsis* (c-a), *Phycosiphon* (c-a), *Rhizocorallium* (m-a), *Chondrites* (r-m), *Schaubcylindrichnus* (m), *Siphonichnus* (r), *Palaeophycus* (m), *Thalassinoides* (r-m), *Teichichnus* (m-c), *Asterosoma* (r), and *Planolites* (m-c). Ancillary elements of the suite include *Arenicolites* (vr), *Bergaueria* (vr), *Rosselia* (vr), *Skolithos* (vr), *Diplocraterion* (vr) and *Ophiomorpha* (r). These ichnogenera show uniform distributions, however due to the overall cleaning- and coarsening- upward trend of this facies, two changes in the ichnological suite can be observed. Trace fossils such as *Diplocraterion,* muddy *Skolithos,* and *Cylindrichnus* become more common in the upper portions of Facies 3, commonly cross-cutting the aforementioned suite (Figures 3.6.B and 3.6.D). There is also a shift seen in the dominant members of the suite, *Zoophycos* and *Helminthopsis* are most abundant at the base whereas *Rhizocorallium, Phycosiphon* and *Teichichnus* become more abundant towards the top. The sandstone beds display a slightly modified, more weakly bioturbated trace fossil suite, dominated by *Diplocraterion*, *Phycosiphon*, fugichnia, *Teichichnus*, *Skolithos*, and *Ophiomorpha.*

Interpretation:

The most characteristic feature of Facies 3 is the exceptionally diverse ichnological suite and intense bioturbate texture, consistent with the archetypal *Cruziana* ichnofacies. This assemblage is indicative of a well-oxygenated substrate with both deposited and suspended food resources. The remnant low-angle wavy parallel lamination present in the rare sandstone beds is interpreted to be hummocky cross-stratification deposited by storm-induced oscillatory currents. The lack of smaller (0.5 - 5 cm) tempestites in Facies 3 is due to higher proportions of burrow types capable of

Figure 3.5. Facies 3: Pervasively bioturbated muddy sandstone and silty sandstone.

Upper Offshore

A) Typical appearance of lower portions of Facies 3, interpreted to represent deposition in the distal upper offshore. Note the approximately even distribution of sand (with the exception of burrow fills) and complete biogenic homogenization. Trace fossils include *Rhizocorallium* (Rh), *Phycosiphon* (Ph), *Helminthopsis* (He), *Thalassinoides* (Th), *Schaubcylindrichnus freyi* (Sch), and ?*Asterosoma* (As). Well 11-33-71-12W6, depth 1221.9m.

B) A bioturbate texture dominated by deep-tier *Zoophycos* (Zo), a common occurrence in offshore deposits. This type of biogenic overprinting would make any quantitative analysis of bioturbate textures impossible. Well 14-25-73-13W6, depth 943.78m.

C) Large, robust *Rhizocorallium* (Rh), *Thalassinoides* (Th), *Zoophycos* (Zo), and ?*Asterosoma* (As). Well 08-30-75-11W6, depth 838.4m.

D) Trace fossils of the distal upper offshore. *Zoophycos* (Zo), *Phycosiphon* (Ph), *Schaubcylindrichnus freyi* (Sch), *Helminthopsis* (He). Well 14-25-73-13W6, depth 944.8m.

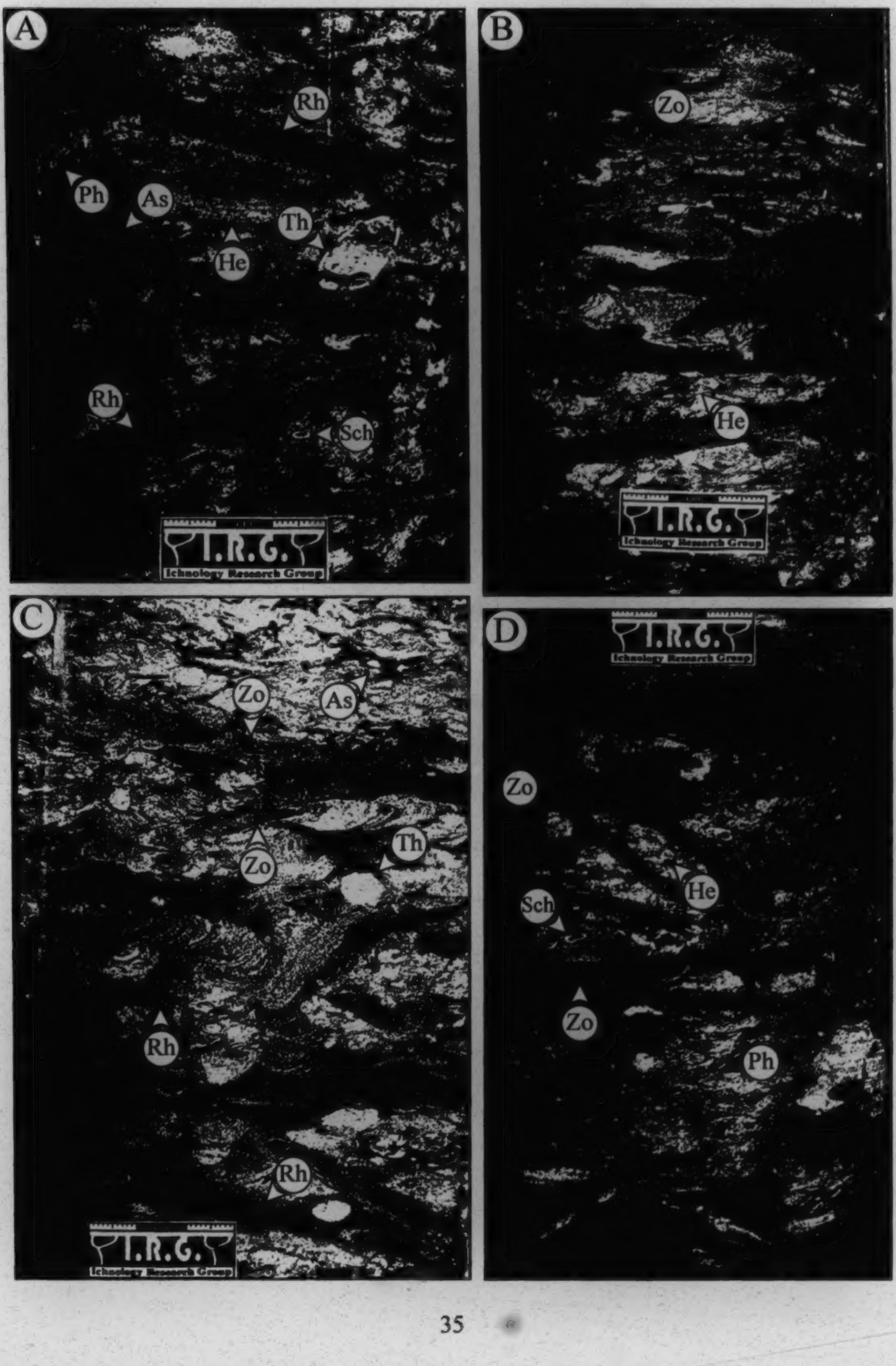
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Figure 3.6: Facies 3: Pervasively bioturbated muddy sandstone and silty sandstone.

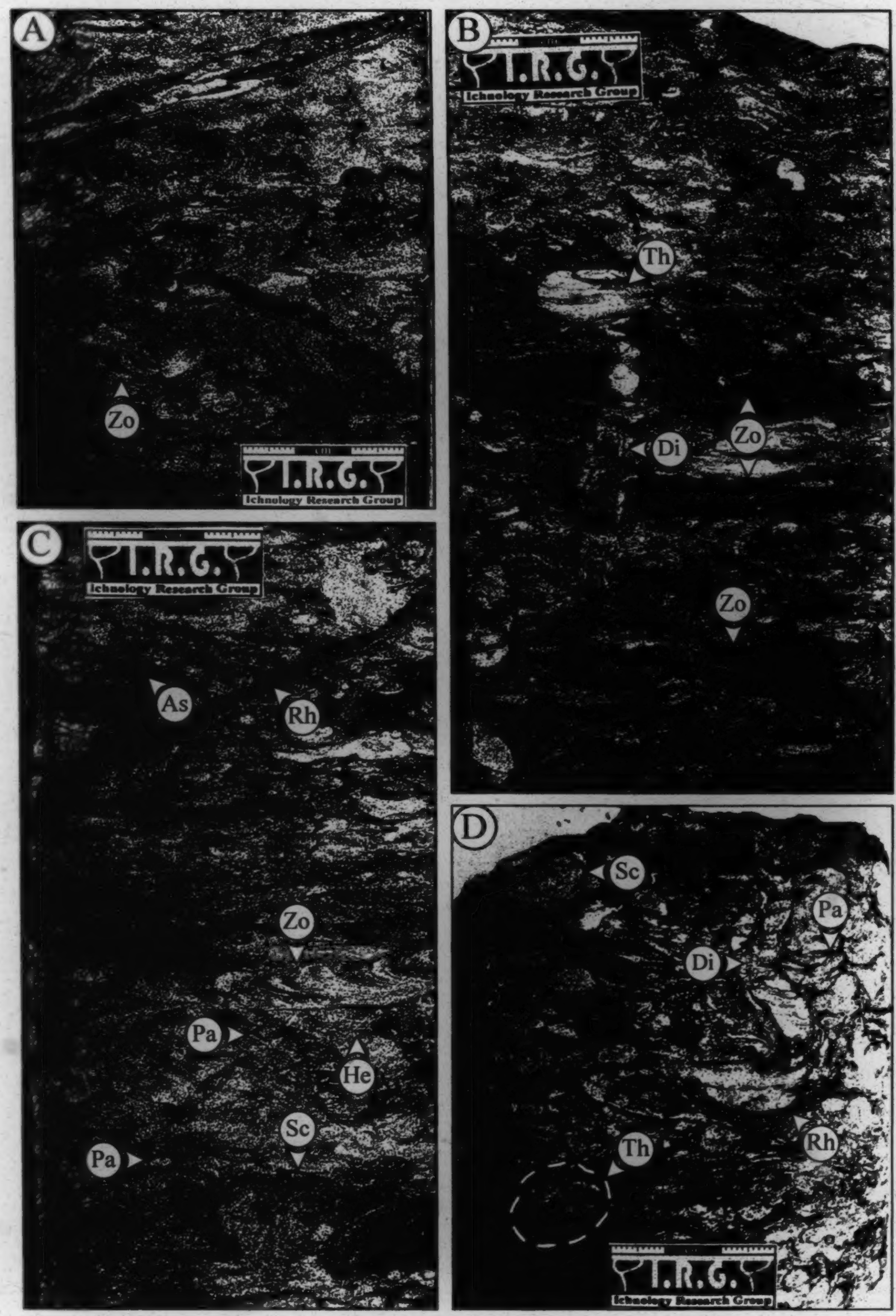
Upper Offshore

A) Highly migratory, chaotic *Zoophycos* (Zo), a common occurrence in the proximal upper offshore. Well 07-26-74-9W6, depth 756.8m.

B) A distinguishing feature of the proximal upper offshore is the incorporation of elements typically associated with the *Skolithos* ichnofacies into the fair-weather ichnological assemblage of the archetypal *Cruziana* ichnofacies. Exemplified here by thin *Diplocraterion* (Di) shafts cross-cutting *Zoophycos* (Zo). Well 16-11-76-11W6, depth 664.52m.

C) Typical appearance of the proximal upper offshore in the Doe Creek Member. This piece clearly shows the distinction between *Scolicia* (Sc), *Zoophycos* (Zo), and *Rhizocorallium* (Rh). Also present are *Palaeophycus* (Pa), *Helminthopsis* (He), and ?*Asterosoma* (As). Well 06-25-75-10W6, depth 704.2m.

D) Typical appearance of the proximal upper offshore – lower shoreface transition. There is a noticeable decrease in the amount of stratal deposit feeding structures such as *Zoophycos* and grazing/foraging structures such as *Helminthopsis* and *Phycosiphon*. Trace fossils present include *Diplocraterion* (Di), *Scolicia* (Sc), *Thalassinoides* (Th), *Palaeophycus* (Pa), and a diminutive *Rhizocorallium* (Rh). Well 07-25-74-11W6, depth 845.7m.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greater vertical penetration such as *Zoophycos*. Burrows such as these could completely rework storm beds unless the beds are of sufficient thickness. These features are indicative of deposition near, but below fair-weather wave base, consistent with the upper offshore environment.

The upper offshore facies of the Doe Creek Member are generally more variable that the lower offshore (Facies 1B and 2) in terms of sedimentological characteristics and contain a more diverse ichnological signature. This variability is largely due to the greater degree of storm and wave influence in the water column and on the substrate (Pemberton *et al.*, 2001). The upper offshore deposits of the Doe Creek Member can be informally subdivided into "proximal" and "distal" settings based on the nature and/or presence of suspension feeding structures such as *Skolithos, Arenicolites,* and *Diplocraterion.*

Sedimentologically the "distal" upper offshore generally displays intensely bioturbated silty and sandy shales (Figure 3.5). These silty and sandy shales are typically bioturbated to such a degree that primary sedimentary structures are completely destroyed. Sandstone beds exhibiting an upward increase in bioturbation intensity (lam-scram) do occur, representing tempestites subsequently colonized by opportunistic species and recolonized by the previous fair-weather suite. Burrowing in the "distal" upper offshore is typically intense, very diverse, and displays an even distribution of ichnogenera. Ichnogenera include *Planolites, Teichichnus, Palaeophycus, Thalassinoides, Helminthopsis, Zoophycos, Phycosiphon, Chondrites, Rhizocorallium, Asterosoma, and Scolicia.* Forms such as *Diplocraterion, Skolithos, Siphonichnus,* and *Arenicolites* are found only associated with the sandy tempestites.

The "proximal" upper offshore, while still dominated by grazing and foraging structures, does display the integration of limited suspension feeding structures such as *Diplocraterion*, *Arenicolites*, and *Skolithos* in the fair-weather suite (Figure 3.6). The incorporation of suspension-feeding trophic strategies within the fair-weather deposits of the upper offshore indicates deposition near fair-weather wave base. In shallower water depths, moderate and minor storm events may be able to induce oscillatory currents on the ocean floor. The increased agitation of the water column by fair-weather wave processes or storm events would maintain a suspended food supply and water circulation to allow for limited amounts of suspension feeders in the "proximal" upper offshore. These suspension feeding structures along with other ichnogenera typically associated with the higher energy *Skolithos* ichnofacies such as *Teichichnus, Rosselia, Arenicolites,* and vertical *Ophiomorpha* typically cross-cut the archetypal *Cruziana* ichnogenera except where deep tier structures such as *Zoophycos* are still prevalent (Figure 3.6.B).

3.2.5 Facies 4: Interlaminated mudstone, siltstone, and sandstone.

Lithology and Sedimentary Features:

Facies 4 is characterized by thin beds of laminated mudstone, siltstone, and lower very fine-grained sandstone, with rare, sharp-bounded, organic-rich claystone beds ranging in thickness from <1cm to 3cm (Figures 3.7 and 3.8). Facies 4 is dominantly mudstone and siltstone with the sand contents ranging between 10-15% by volume. The sandstone beds range from 1-5 cm thick, are sharp based with diffuse or bioturbated tops, and are characterized by normal grading, low-angle wavy parallel lamination, commonly grading into oscillation ripple, and combined-flow ripple cross-lamination. The oscillation ripple and combined-flow ripple cross-lamination can be aggradational in character. Unidirectional current ripple cross-lamination is also common. These sandstone beds are typically draped by the aforementioned organic-rich mudstone or claystone beds which are typically 1-3 cm thick. Load-cast features, soft-sediment deformation, contorted bedding and fluid-escape structures are common. Other features include erosive-based, complex scour and fill structures (Figures 3.7.B and 3.8.C). Finely comminuted organic detritus commonly accentuates sandstone bed laminae. Coal and wood fragments can be seen on bedding planes but is typically most common in the organic-rich mudstone beds which display ubiquitous dull brown to black organic detritus. The organic-rich mudstones also contain small, thin, sand-filled synaeresis cracks, typically subtending from a superjacent sandstone bed. Siderite nodules are common, and the organic-rich mudstone beds are locally siderite cemented.

Ichnology:

Bioturbation intensities in this facies are variable on a bed to bed scale, ranging from low to moderate. The intensities are greatest in the silt- and mud-rich beds and lowest in sandstone and organic-rich mudstone beds. Ichnogenera present include *Phycosiphon* (m-c), *Helminthopsis* (r-m), *Planolites* (m-c), *Chondrites* (r-m), *Zoophycos* (vr-r), *Rhizocorallium* (vr-r), *Teichichnus* (r-m), *Thalassinoides* (r-m), and ?*Scalarituba* (vr) . *Zoophycos* and *Rhizocorallium* tend to be sporadically distributed, occurring as solitary, relatively diminutive forms that rarely cross more than one bedding contact (Figs. 3.7.A, 3.7.D). The sandstone beds commonly display a slightly modified ichnological suite including *Skolithos* (r-m), *Ophiomorpha* (r-m), *Cylindrichnus* (r-m), and fugichnia. The organic-rich mudstone beds are typically pristine and unburrowed with the exception of rare *Planolites* and *Chondrites*.

Figure 3.7. Facies 4: Interlaminated mudstone, siltstone, and sandstone.

Distal Prodelta

A) Typical appearance of the distal prodelta. Note the distinct lack of bioturbation relative to the open marine offshore deposits of Facies 3 and 4. Ichnogenera present include *Planolites* (Pl), *Helminthopsis* (He), and diminutive ?*Zoophycos* (Zo). Well 06-02-0-76-8W6, depth 725.4 m.

B) A moderate-sized gutter cast, a common feature in the prodeltaic deposits of the Doe Creek Member. Well 11-09-75-9W6, depth 716.8 m.

C) A diminutive *Zoophycos* (Zo) in an otherwise weakly bioturbated unit. Note the very fine-grained sandstone stringers (pinstripe lamination) in the large mudstone bed in the center of the photograph. Other trace fossils include *Planolites* (Pl) and *Chondrites* (Ch). Well 07-26-74-9W6, depth 766.52 m.

D) Typical appearance of the distal prodelta, note the poorly defined *Zoophycos* (Zo) and *Thalassinoides* (Th) as well as *Chondrites* (Ch) and synaeresis cracks (Syn). Well 10-01-74-11W6, depth 919.25 m.

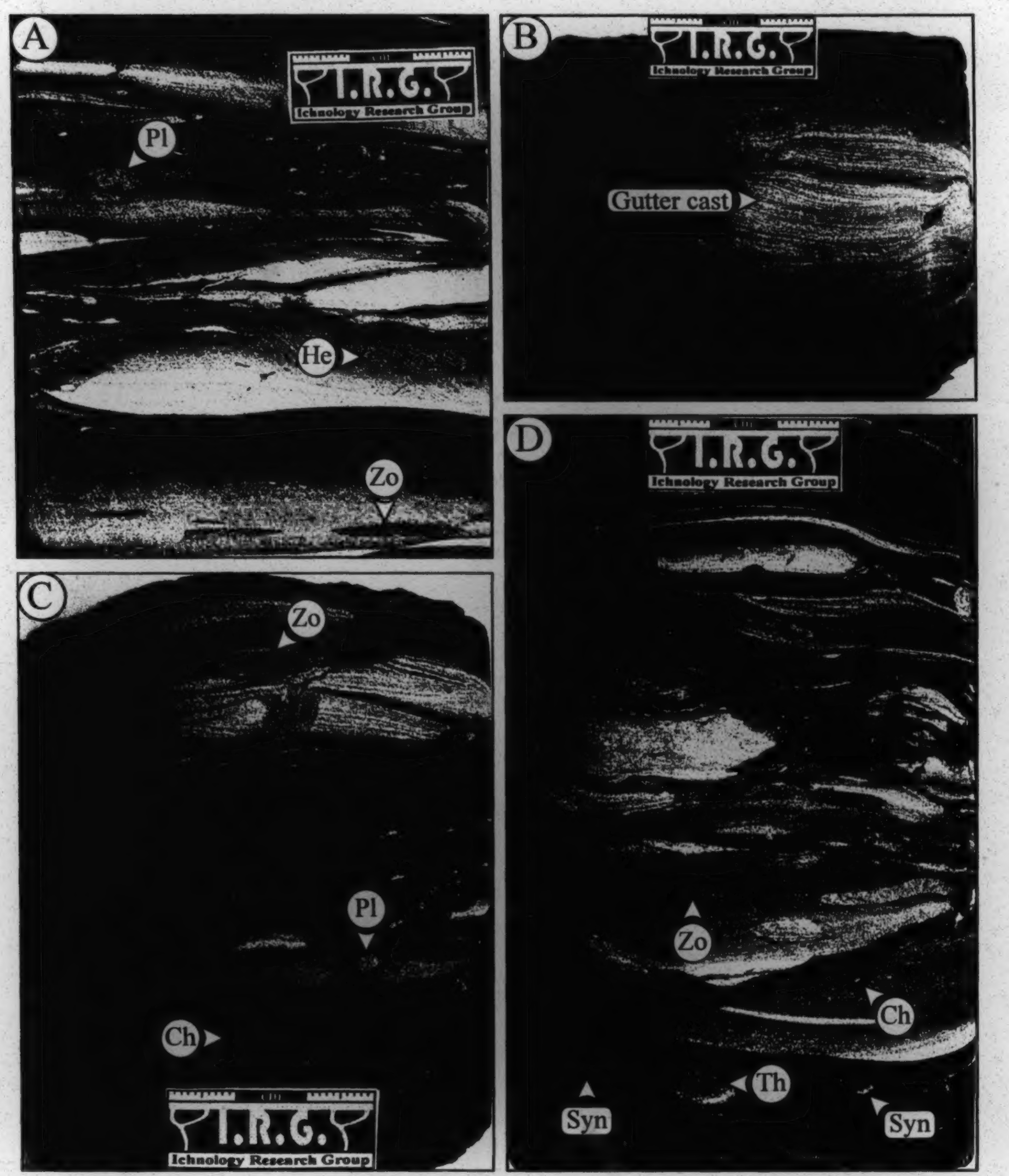
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Figure 3.8. Facies 4: Interlaminated mudstone, siltstone, and sandstone.

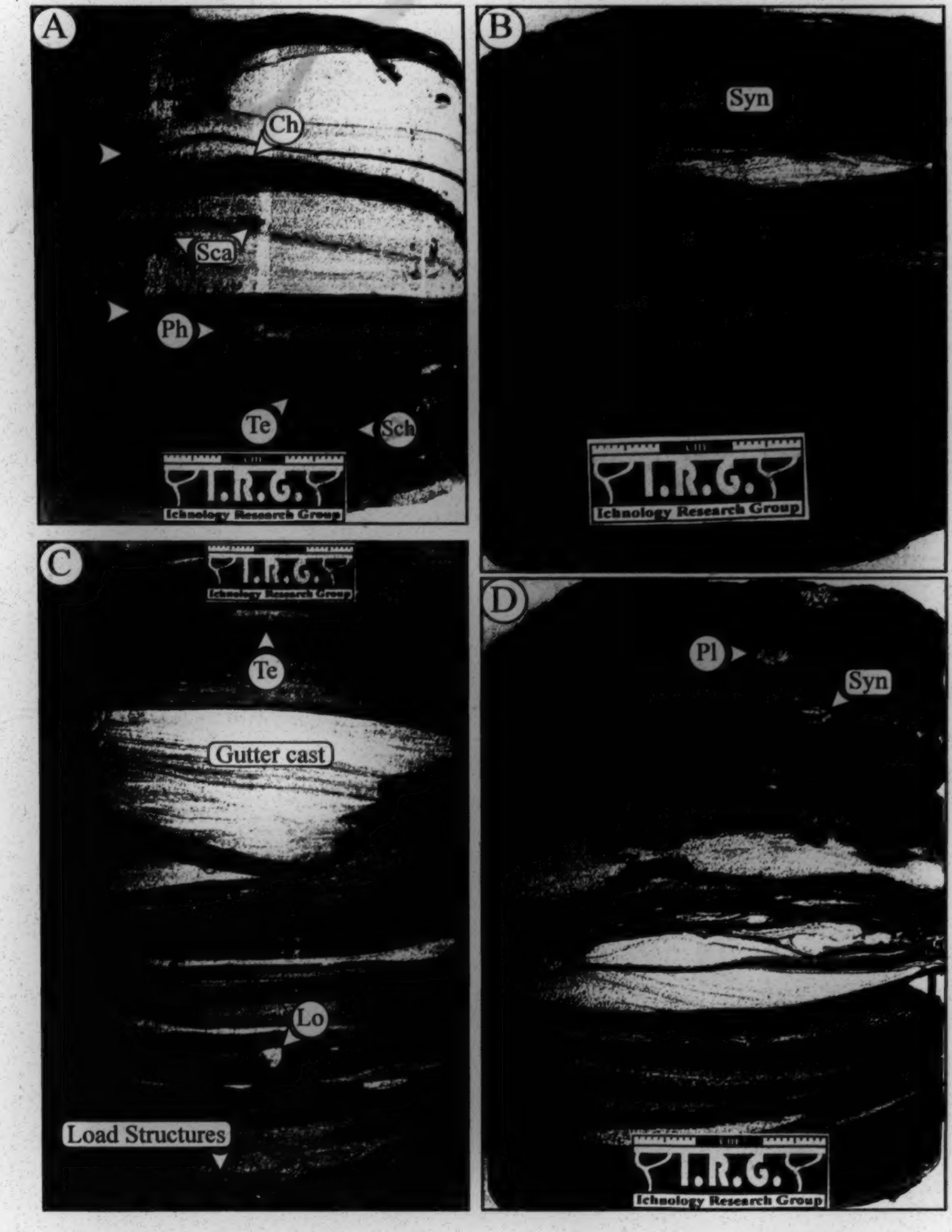
Distal Prodelta

A) This photograph shows the difference between post-storm, organic-rich mud drapes (green arrow), which are typically normally graded and contain sand and silt sized particles, and fluid mud deposits (yellow arrow) which typically are sharp-bounded, do not display graded bedding and are devoid of sand and silt sized particles. Ichnogenera present include *Chondrites* (Ch), *Phycosiphon* (Ph), *Schaubcylindrichnus freyi* (Sch), *Teichichnus* (Te) and ?*Scalaratuba* (Sca). Well 06-02-76-8W6, depth 725.5m.

B) Large synaeresis cracks (Syn) cutting across primary bedding. Microfaulting is also evident, fracturing a normally graded, combined-flow ripple cross-laminated silty sandstone. Note the high total organic content of the mudstone beds in stark contrast to the mudstones and shales seen in Facies 1A, 1B, 2, and 3. 16-34-76-9W6. depth 667.54m.

C) Large gutter cast structure demarcating the base of a tempestite. Note the low bioturbation intensities with ichnogenera including *Teichichnus* (Te) and *Lockeia* (Lo). Loading structures seen at the base of the sandstone bed in the lower portion of the photo indicate the subjacent bed was soupy (water-laden). Well 08-35-76-8W6, depth 571.4m.

D) Typical appearance of the distal prodelta in the Doe Creek Member. Note the combined-flow ripple cross-lamination. *Planolites* (Pl) and syneresis cracks (Syn) are also present. Well 07-26-74-9W6, depth 759.95m.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Interpretation and Discussion:

Facies 4 is similar to Facies 3 lithologically, but shows a marked decrease in bioturbation intensities. Though the ichnological assemblage remains relatively diverse, bioturbation is characterized by a sporadically distributed composite of grazing/foraging and deposit feeding structures. The low-angle, wavy parallel lamination seen in the sandstones is interpreted as small-scale hummocky cross-stratification. The combined-flow ripple and oscillation ripple cross-lamination are inferred to be the result of deposition during the waning flow stage of storms. The aggradational combined-flow ripple and oscillation ripple cross-lamination indicate high sediment load and sedimentation rate. The current ripple cross-lamination represents deposition under unidirectional traction currents induced by failures on the delta front (turbidity currents) or during sustained hyperpycnal discharge. The erosively based scour and fill structures are interpreted to be gutter casts (Whitaker, 1973). The presence of synaeresis cracks in the fine-grained beds is interpreted to have formed in response to the shrinkage of clay minerals associated with fluctuating salinity levels (*i.e.* temporarily reduced) in the water column (Burst, 1965; Plummer and Gostin, 1981). These salinity fluctuations are inferred to be the result of fresh- or brackish-water influx from fluvial discharge. Shallow water portions of deltas (<10 m) can exhibit a consistently brackish water column (MacEachern *et al.*, 2005), whereas the portions of deltas with water depths greater than 10-30 m typically show only periodic salinity fluctuation reaching the sediment-water interface. The subaqueous environments of deltaic successions can also be affected by increased sedimentation rates, event-type sedimentation (*e.g.* delta front turbidites, tempestites, etc.), high water turbidity, and periodic reduced oxygenation (MacEachern *et al.*, 2005). These factors, coupled with salinity reduction of the water column, serve to restrict marine faunal activity, resulting in a stressed, or restricted, ichnological suite.

The sharp-bounded and gradationally-based organic-rich claystone beds are interpreted to be the result of rapid mud deposition either from flocculation and suspension fallout of hypopycnal plume sediment or as hyperpycnal discharge. Dense, sediment-laden plumes are common at the river mouth of delta systems. These plumes can manifest as hypopycnal or hyperpycnal (with much less common homopycnal in marine settings), discharge and can be affected by seasonal and climactic factors, resulting in highly variable deposition (MacEachern *et al.*, 2005). Rivers typically display an increased sediment load during and following major storm events. This may also be the cause of the organic-rich mudstone drapes commonly found capping tempestites. Fluid mud deposits can be recognized by their high organic content representing phytodetrital material carried in the river plume (Rice *et al.*, 1986) and low bioturbation intensities. Fluid mud deposits typically lack silt- and sand-sized particles and are predominantly massive in character showing no discernable sedimentary structures. Organic-rich mudstones resulting from hyperpycnal discharge are deposited primarily by unidirectional traction currents and therefore will tend to display planar lamination and other current generated features. Hyperpycnal mudstones will also tend to contain sand-sized grains, typically localized as sandstone stringers due to the relatively higher hydraulic energies.

The ichnological suite of Facies 4 represents a restricted and distal expression of the *Cruziana* ichnofacies, indicative of deposition below fair-weather wave base, in a setting subject to common environmental fluctuations consistent with deposition in a distal subaqueous delta setting (*cf.* Bann and Fielding, 2004; MacEachern *et al.*, 2005; Coates and MacEachern, 1999, 2000). The fine-grained, interlaminated character of this facies is consistent with deposition in an open-marine, storm-influenced lower offshore non-deltaic shelf. However, the stressed ichnological suite and indications of fluvial influence suggest that deposition took place in a distal prodelta environment.

3.2.6 Facies 5: Interbedded sandstone, claystone, and siltstone

Lithology and Sedimentary Features:

Facies 5 consists of discrete claystones and mudstones, sandy siltstone, and interbedded lower and upper very fine-grained sandstone in approximately equal proportions (Figures 3.9 and 3.10). The sandstone and sandy siltstone beds are lenticular, sharp based, normally graded, and vary from 0.5 – 5 cm thick, and commonly thicken upward through the facies. Sedimentary structures in the sandstone, siltstone and claystone interbeds include lenticular and wavy bedding comprising low-angle, wavy parallel cross-lamination, wave-ripple cross lamination, rare small-scale hummocky cross stratification, combined-flow ripple cross-lamination, oscillation ripple cross-lamination, and massive bedding. Aggradational combined-flow ripple and oscillatory ripple forms are common. In most cases individual sandstone beds are sharp-based, fine upward, and are often capped by an organic-rich mudstone drape. The claystone and mudstone beds are dark brown to black in color owing to a high total organic content, are commonly massive, and display sharp to scoured bases. The presence of these sharp-bounded, dark claystones causes the characteristic "sharply" interlaminated and/or interbedded appearance of this facies. Deformation structures are common throughout Facies 5, and are most commonly associated with the thicker sandstone interbeds. Deformation features include load structures at the base of the sandstone beds, contorted bedding, convolute bedding, and micro-faulting. Other distinguishing characteristics include centimeter-scale to rare decimeter-scale gutter casts, common synaeresis cracks, siderite nodules, and sideritized beds.

Ichnology:

Bioturbation is sporadically distributed, with many intervals completely unburrowed. Bioturbation intensities are typically low to moderate. The trace fossil suite of Facies 5 displays a reduced abundance and diversity of traces. The thicker sandstone beds and the organic-rich mudstone beds display the lowest bioturbation intensities. Ichnogenera include *Planolites* (c), *Chondrites* (c), *Phycosiphon* (m-c), *Thalassinoides* (r-m), *Helminthopsis* (r-m), fugichnia (r), *Palaeophycus* (r), *Teichichnus* (r-m), *Rhizocorallium* (r-m), *Zoophycos* (r), *Schaubcylindrichnus freyi* (vr), *Taenidium* (vr), *Scolicia* (vr), ?*Asterosoma* (vr), and *Lockeia* (vr). *Skolithos* (vr), *Cylindrichnus* (vr) and fugichnia are present but only associated with the thicker sandstone beds. The fully marine ichnogenera such as *Zoophycos* (Wetzel and Werner 1981; Löwemark and Schäfer 2003) display an extremely sporadic distribution, occurring as solitary, diminutive forms that rarely cross bedding contacts. In some instances, *Zoophycos* and *Rhizocorallium* are seen to selectively track clay and organic-rich laminae or beds (Figure 3.9.C).

Interpretation:

Facies 5 displays broad similarities to a storm-influenced upper offshore setting. The sandstones comprising low-angle wavy parallel lamination are interpreted to represent hummocky cross-stratified storm deposits. The gradation of HCS to combined-flow ripple cross-lamination and oscillation ripple cross lamination is consistent with waning flow deposits of tempestites. The tempestites in Facies 5 are typically thicker than those found in Facies 4, and are also characteristically capped by organic-rich mudstones which are also thicker. These mudstones display high amounts of visible organic detritus in the form of coaly and woody fragments as well as macerated plant debris. These mudstones are interpreted to be deposits reflecting heightened fluvial discharge during and after a storm event.

Facies 5 displays restrictions in ichnological diversity and abundance, resulting in a stressed expression of the archetypal *Cruziana* ichnofacies. This is manifested as a reduction in the numbers of individual burrows as well as overall bioturbation intensity. The restriction of trace fossils such as *Zoophycos* and *Rhizocorallium* both in numbers and spatially, indicates an environment that exhibited periodic fluctuations in the degree

Figure 3.9. Facies 5:Interbedded sandstone, claystone, siltstone.

Proximal Prodelta

A) An example of moderate bioturbation intensities in the proximal prodelta of the Doe Creek Member. Ichnogenera present include *Ophiomorpha* (Op), *Helminthopsis* (He), *Schaubcylindrichnus freyi* (Sch), *Planolites* (Pl), and *Palaeophycus* (Pa). Well 11-33-71-12W6, depth 1219.35m.

B) Typical appearance of the proximal prodelta in the Doe Creek Member. Ichnogenera present include *Teichichnus* (Te) and *Chondrites* (Ch), note the small synaeresis cracks (Syn) in the mudstone beds near the top of the photo. Well 08-01-79-9W6, depth 313.5m.

C) A moderate sized tempestite bed is burrowed by a mud-rich *Zoophycos* (Zo). Note the *Zoophycos* is selectively tracking micaceous/organic rich laminations. This particular feature is interpreted to represent subsurface deposit-feeding behavior of the *Zoophycos* organism. Well 10-02-73-10W6, depth 960.95m.

D) Examples of turbidites in the proximal prodelta. Note the organic-rich mudstone capping the normally graded tempestite. This is inferred to represent post-storm, flood related deposition. Ichnogenera present include *Zoophycos* (Zo), *Planolites* (Pl), *Helminthopsis* (He), *Phycosiphon* (Ph), and *Teichichnus* (Te). Well 14-34-74-10W6, depth 710.6m.

E) Intense soft-sediment deformation, consistent with rapid deposition, in the proximal prodelta. Trace occurrence of *Helminthopsis* (He) in the lower portion of the photo. Well 16-12-73-11W6, depth 949.6m.

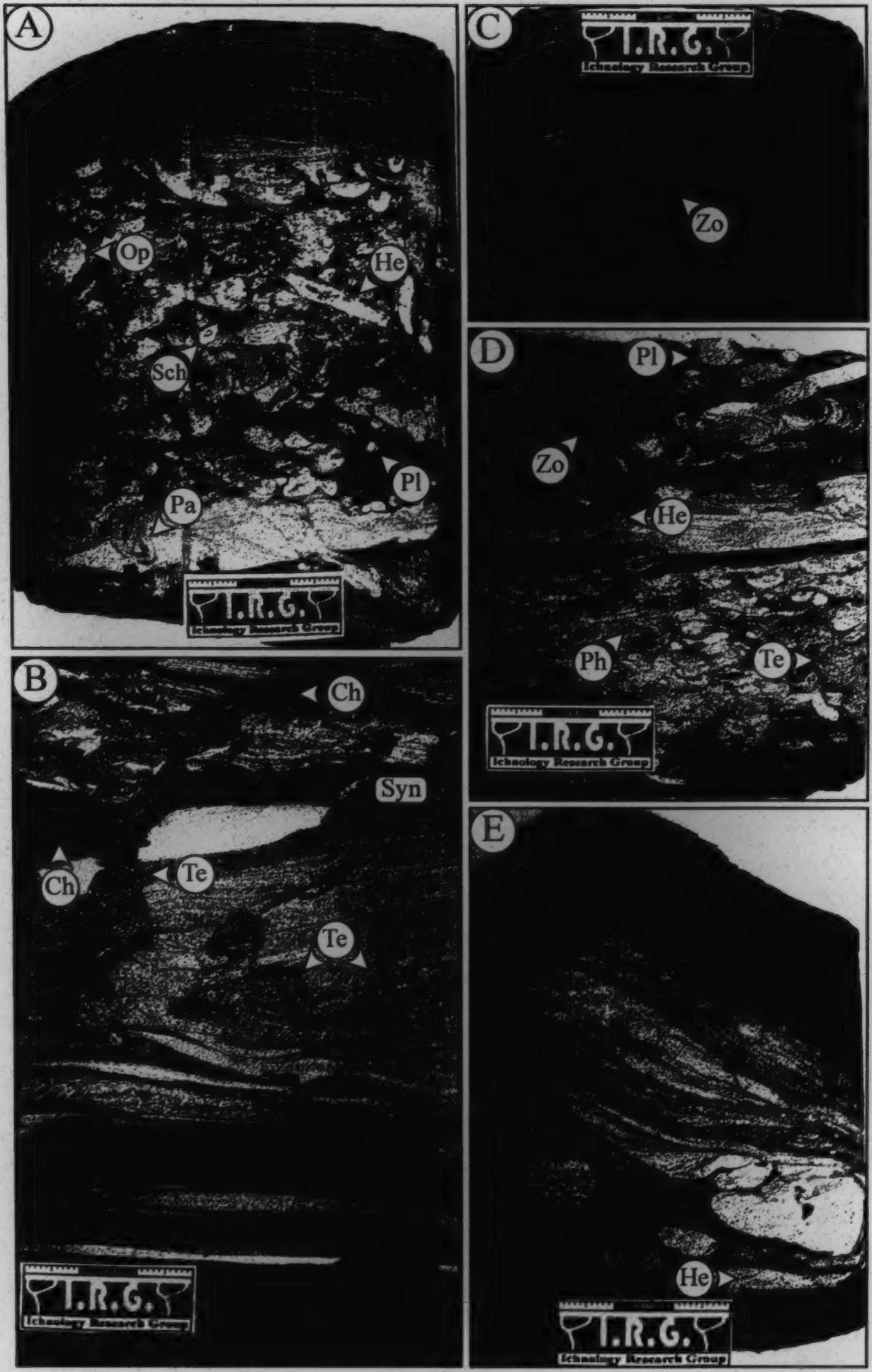
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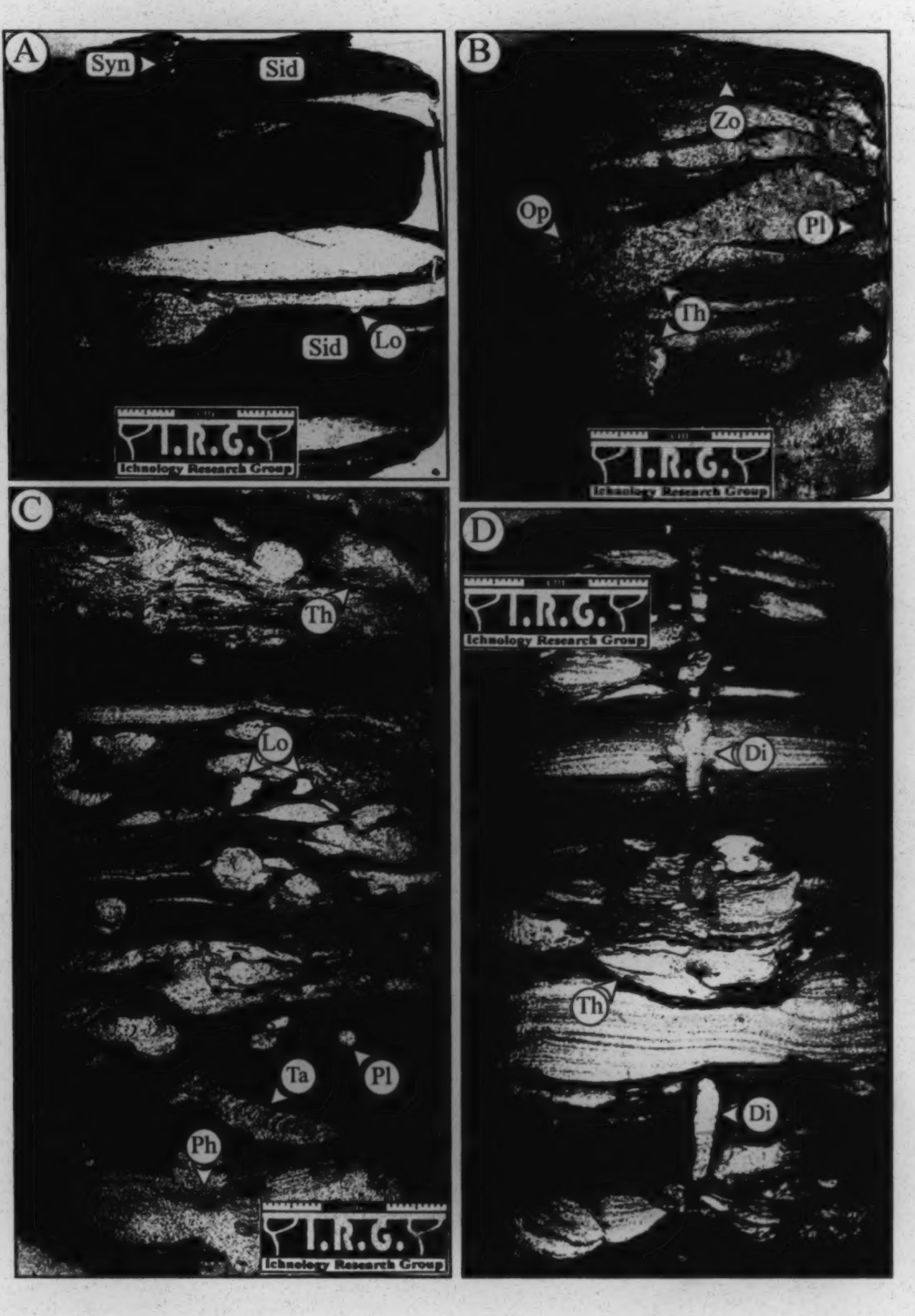
Figure 3.10. Facies 5: Interbedded sandstone, claystone, siltstone.

Proximal Prodelta

A) Typical appearance of the proximal prodelta. Note the extremely low bioturbation intensity, sideritization of organic-rich mudstone, and the synaeresis cracking (Syn). Possible ?*Lockeia* (Lo) or hypichnial groove. Well 10-02-73-10W6, depth 960.65m.

B) Examples of trace fossils in the proximal prodelta. Note the diminutive, mud-rich *Zoophycos* (Zo) in the upper portion of the photograph. Other ichnogenera present include *Thalassinoides* (Th) and *Planolites* (Pl) and *Ophiomorpha* (Op). Well 06-36-74-10W6, depth 728.7m.

C) and D) Examples of proximal prodelta deposits in the Doe Creek Member. Note the dominance of simple forms of ichnogenera and low bioturbation intensities. Ichnogenera present include *Thalassinoides* (Th), *Planolites* (Pl), *Phycosiphon* (Ph), ?*Lockeia* (Lo), ?*Taenidium* (Ta), and *Diplocraterion* (Di). C) Well 16-28-77-13W6, depth 466.33m. D) 16-28-77-13W6, depth 466.33m.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of hostility to faunal colonization. This is interpreted to reflect the episodic flux of fresh- or brackish-water to the prodelta, due to factors controlling fluvial output. The behavior of some *Zoophycos* trace-makers noted in Facies 5 of selectively tracking organic-rich laminations in the sandstone beds is interpreted to represent discriminatory, inter- and intra-stratal deposit feeding. The organic-rich mudstones present in Facies 5 show similar restrictions in bioturbation to those of Facies 4. Typically only *Chondrites* and *Planolites* are found within these mudstones. The high total organic content within these mudstones would likely have been aggressively colonized by bacteria leading to localized anoxic/ dysaerobic and reducing conditions. These beds would then be exploited by organisms capable of feeding on the bacteria in a reducing environment, such as *Chondrites*. Similar observations and interpretations have been postulated in organic-rich mudstones in the Jurassic Posidonieschiefer Formation of Germany (Bromley and Ekdale, 1984); the Turonian/Coniacian Cardium Formation of Alberta (Vossler and Pemberton, 1988, 1989); the Bow Island Formation of southern Alberta (Raychaudhuri and Pemberton, 1992; Raychaudhuri, 1994); the Albian Cadotte Member of the Peace River Formation (Saunders, *et al.*, 1994); the Cenomanian Dunvegan Formation (Gingras, *et al.*, 1998); and in Permian units in the Denison Trough of Queensland, Australia (Bann and Fielding, 2004).

The increased numbers and thickness of storm beds compared to Facies 4 indicates depositional positions equivalent to that of the upper offshore. However, the aforementioned physical and ichnological characteristics of Facies 5 point to deposition in a proximal prodelta setting.

3.2.7 Facies 6: Interbedded sandstone, bioturbated sandstone, and claystone

Lithology and Sedimentary Features:

Facies 6 typically conformably overlies Facies 5, and consists of interbedded very fine- to fine-grained sandstones and claystones with sand contents ranging from 50 to 85 percent (Figures 3.11 and 3.13). The sandstone beds occur as discrete, sharp-based, laminated, clean sandstone beds and bioturbated sandstones ranging in thickness from 3 to 15 cm and tend to become thicker upward within the Facies. Dominant sedimentary structures within the sandstone beds include low-angle planar parallel lamination, wavy parallel lamination, and convex upward lamination. Other structures commonly found include oscillation ripple, and combined-flow ripple cross-lamination which is locally aggradational in nature (Figures 3.11.B, 3.12.A, 3.12.B) and current ripple cross-lamination. The laminae seen in the sandstone beds are commonly accentuated by finely comminuted organic detritus. Coaly fragments and intraformational rip-up clasts in the form of angular mudstone and sideritized mudstone can be found on bedding planes and truncation surfaces, and to a lesser degree, on lamination surfaces. Complex, sand-filled scour and fill structures are common (Figures 3.11.B and 3.12.B). In some instances, the low-angle parallel laminated sandstone beds are internally comprised of repetitive, normally graded, thin (3-8 mm) sandstone beds (i.e. graded rhythmites) (Figure 3.11.A). Intercalated organic-rich claystones and mudstones are typically seen to drape the sandstone beds in a similar manner to that described for Facies 4 and Facies 5. They occur as thin (<3cm) beds that are predominantly massive but can display weak lamination locally, and can be completely siderite cemented (Figure 3.12.C). Within the claystone beds carbonaceous detritus, small coal fragments, and woody material are ubiquitous. Sand filled synaeresis cracks, which are typically ptygmatically folded, can occur in these claystone beds, originating and subtending from overlying sandstone beds. Some sandstone beds exhibit oil-stains, patchy calcite cement, and minor glauconite-rich laminae. Soft-sediment deformation features such as contorted and convolute bedding, loading at the base of sandstones, and micro-faulting are prevalent throughout.

Ichnology:

Bioturbation intensities in Facies 6 are generally low to moderate and burrowing is sporadically distributed with many beds remain completely unburrowed. The thicker sandstone beds can display lam-scram texture locally, and display a trace fossil suite dominated by *Skolithos* (m), *Ophiomorpha* (r-m), fugichnia (m-c), *Diplocraterion* (r), *Cylindrichnus* (r), and *Arenicolites* (vr). The trace fossil suite of the bioturbated sandstone beds contains a higher proportion of dwelling burrows of inferred deposit feeders and passive carnivores. Ichnogenera include *Planolites* (c), *Teichichnus* (m), *Palaeophycus* (r-m), *Skolithos* (m), *Ophiomorpha* (r-m), fugichnia (m-c), *Diplocraterion* (r-m), *Cylindrichnus* (r), *Arenicolites* (vr-r), *Rosselia* (r), *Phycosiphon* (r-m), *Helminthopsis* (r), *Rhizocorallium* (r), *Zoophycos* (vr), and *Asterosoma* (vr). *Rhizocorallium* and *Zoophycos* commonly occur as diminutive, spatially restricted forms, that appear to preferentially follow muddy, organic-rich laminae and beds similar to those seen in Facies 5. The organic-rich claystone beds exhibit very rare *Arenicolites* , and exceedingly rare, solitary and diminutive forms of *Planolites*, and *Chondrites*.

Interpretation:

The low-angle parallel lamination, wavy parallel lamination, and convex upward lamination are interpreted to represent different expressions of hummocky

Figure 3.11. Facies 6: Interbedded sandstone, bioturbated sandstone, and claystone.

Distal Delta Front

A) Typical appearance of the distal delta front. Note the graded rythmites (green arrow) visible in the lower portion of the laminated sandstone bed. Trace fossils present include *Skolithos* (Sk), *Macaronichnus segregatis* (Ma), *Zoophycos* (Zo), *Planolites* (Pl), and *Phycosiphon* (Ph). Well 10-01-74-11W6, depth 900.5m.

B) A large gutter cast, a feature common in the distal delta front, cutting across the sharply interbedded sandstone and mudstone. Note the aggradational oscillatory ripple in the center of the photograph. Ichnogenera present include ?*Cylindrichnus* (Cy) and *Planolites* (Pl). Well 11-33-71-12W6, depth 1218.9m.

C) Example of distal delta front deposits of the Doe Creek Member. Note the predominance of wave-formed structures in the sandstones and the black, organic-rich mudstone partings. Trace fossils present include *Rhizocorallium* (Rh), *Teichichnus* (Te), *Chondrites* (Ch), and fugichnia (Esc). Vertical striations on the core are scratches incurred during core retrieval. Well 08-09-73-12W6, depth 1018.5m.

D) Examples of storm induced mud deposition. Note the thick organic-rich mudstone draping the hummocky cross-stratified to wave-rippled sandstones. These mudstone drapes are common features of tempestites in deltaic settings. Trace fossils include *Ophiomorpha* (Op), *Chondrites* (Ch), and *Zoophycos* (Zo). Well 16-12-73-11W6, depth 953.53m.

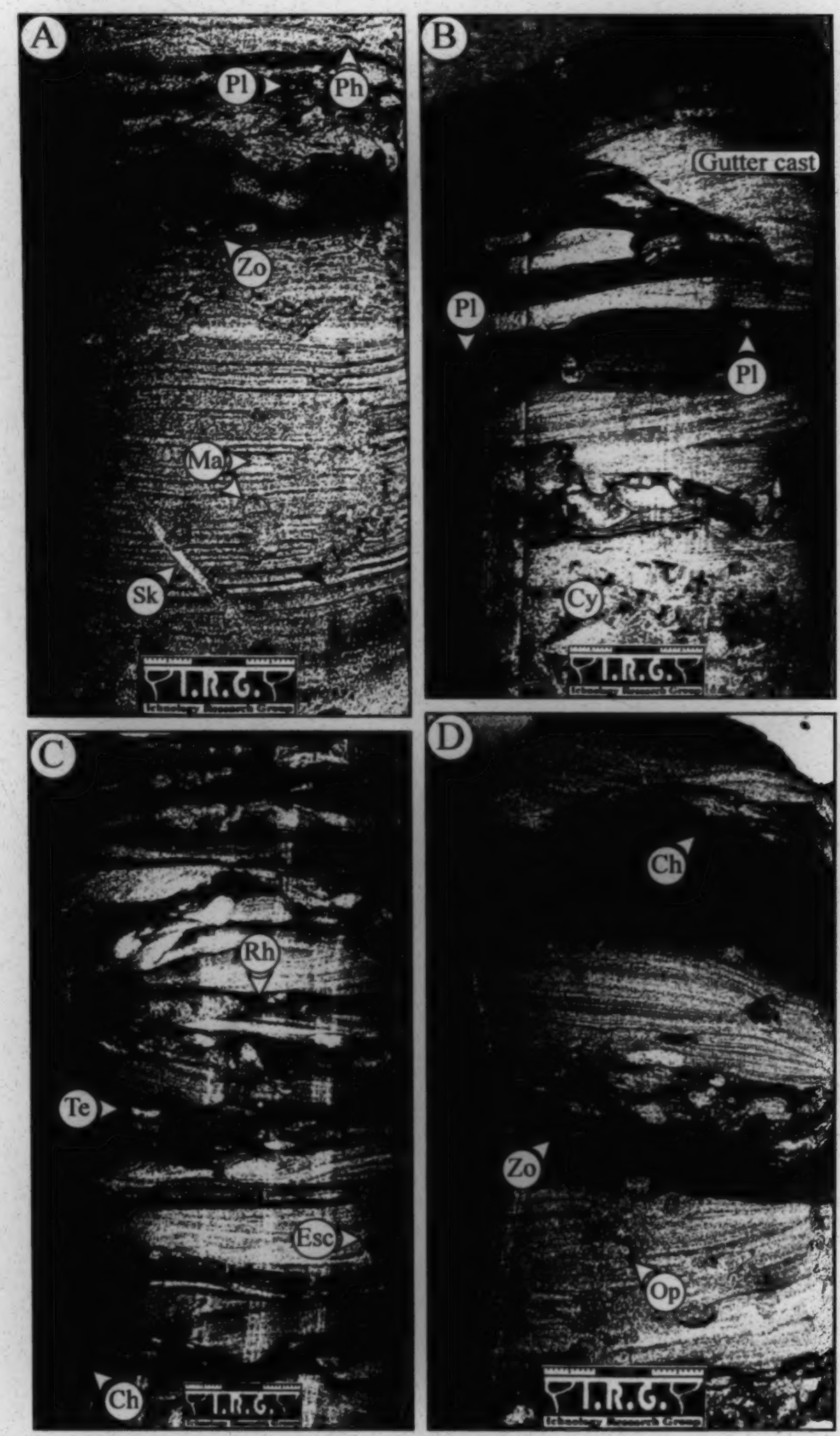
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Figure 3.12. Facies 6: Interbedded sandstone, bioturbated sandstone, and claystone.

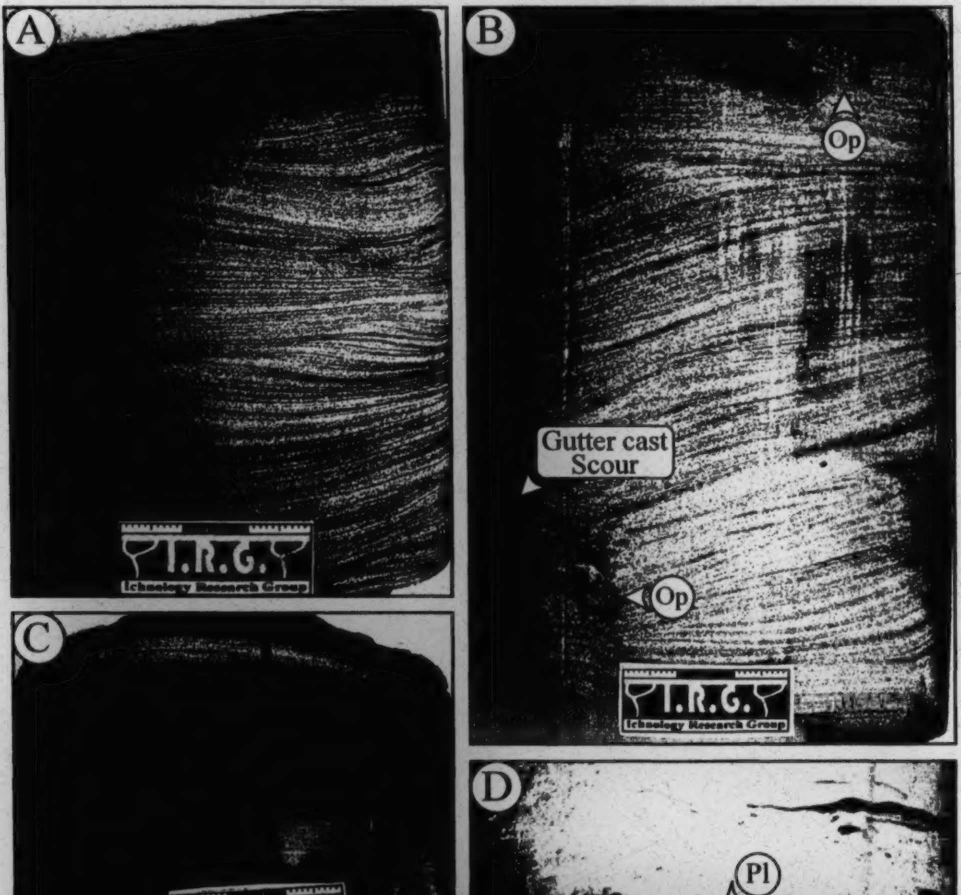
Distal Delta Front

A) Low-angle parallel lamination transitioning to aggradational, combined-flow ripple cross-lamination. Succession is capped by a massive to weakly-laminated, organic-rich mudstone. Well 16-12-73-11W6, depth 949.85m.

B) A complex set of scour-and-fill structures transitioning into aggradational combined-flow ripple cross-lamination. Note the base of the main gutter cast, basal scour in the lower left. *Ophiomorpha* (Op) is present in the sandstone. Well 11-33-71-12W6, depth 1239.7m.

C) A large tempestite bed in the distal delta front. Note the sideritized mudstone rip-up clasts along the basal scour, leading to swaley cross-stratified sandstone, capped by a large sideritized mudstone bed. Well 07-26-74-9W6, depth 760.1m.

D) A similar tempestite bed to figure 2.12.C, however the organic-rich mudstone has remained unmineralized. Note the *Arenicolites* (Ar) and *Planolites* (Pl) within the mudstone. *Planolites* (Pl) preserved as exichnion at the upper bedding contact. Well 14-35-74-10W6, depth 707.38m.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cross stratification and swaley cross-stratification. The sharp-based character of these sandstones implies erosional emplacement via storm wave action. The combined-flow ripples and oscillatory ripples are inferred to have been the result of waning flow during storm abatement. The oscillatory ripples are also consistent with reworking of the tops of tempestites by fair-weather processes. The bioturbated sandstone intervals are likely the result of relatively low energy (compared to the tempestite sandstones) fair-weather sandstone deposition which would allow infaunal colonization. Interbedded hummocky cross-stratified sandstones and bioturbated sandstones are typical of deposition in a storm-influenced lower shoreface environment. However, numerous characteristics of this facies, both sedimentological and ichnological, differ markedly from and open-marine shoreface environment. The abundant carbonaceous detritus which demarcates stratification and lamination planes suggest there was ample organic debris in the local environment of deposition. The presence of convolute bedding, contorted bedding and micro-faulting suggests periods of rapid deposition of water-laden sediment. Beds comprising planar parallel stratification, grading to current ripple cross-lamination through silty mudstone, capped by organic-rich mudstone, resemble BCD turbidites (Bouma, 1963). These are inferred to result from density driven underflows caused by increased fluvial discharge in response to high precipitation rates that accompany storm events (Coleman, 1981; Wright, *et al.*, 1988; Leithold, 1989; Raychaudhuri and Pemberton, 1992; Raychaudhuri, 1994; MacEachern *et al.*, 2005). Some organic-rich claystone and mudstone beds may also be the result of rapid flocculation of riverine-derived material, resulting in fluid mud beds collecting in relative topographic lows. These claystones and mudstones, irrespective of their depositional nature, reflect rapid introduction of organic material and debris. This organic material would be oxidized via bacterial mediation, which could result in anoxic/dysaerobic conditions to occur locally. Synaeresis cracks are interpreted to be the result of salinity fluctuations within the water column associated with fresh- or brackish-water influx. The combination of rapid and fluctuating sedimentation rates, salinity variations, and local anoxic/dysaerobic conditions would serve to preclude biogenic activity. This manifests as the sporadic distribution of bioturbation and the stressed expression of the mixed *Skolithos-Cruziana* ichnofacies seen in Facies 6. The mixed *Skolithos-Cruziana* ichnofacies reflects *in loco* fluctuations in energy levels (Pemberton and Frey, 1984; MacEachern and Pemberton, 1992; Pemberton and MacEachern, 1997). The general paucity of suspension-feeding ichnogenera in comparison to an open-marine shoreface setting is attributable to inferred high water turbidity associated with river delta plumes, similar to postulations made by Moslow and Pemberton, 1988; Saunders *et al.*, 1994; Gingras *et al.*, 1998; Coates and MacEachern, 1999; MacEachern *et al.*, 2005. The sedimentological features, coupled with bioturbate textures seen in Facies 6, are interpreted to reflect deposition in a storm-influenced distal delta front environment.

3.2.8 Facies 7A: Thickly bedded, laminated sandstone

Lithology and Sedimentary Features:

The sandstone in Facies 7A has an average grain size of upper very fine to lower fine sand, with less common occurrences of lower medium sand. The sandstone beds range in thickness from 10 cm to 1.0 m, average approximately 30 cm to 40 cm, and are commonly amalgamated into bedsets ranging from 0.5 to 1.3 m thick. The beds comprise large-scale, low-angle planar parallel to undulatory cross-lamination (typically between 3-13°), passing upwards into smaller scale, wavy parallel, convex-upward laminations (Figures 3.13, 3.14, 3.15). Current ripples, combined-flow ripples, and oscillation ripples are rare but are present locally, the latter two typically displaying moderate amounts of aggradation (Figure 3.14.C). High-angle (16° or greater) cross bedded units exhibiting an upward increase in the angle of lamination occur in the upper portions of this facies, typically associated with the medium grained sandstones (Figures. 3.14.A). Graded rhythmites, similar in character to those described in Facies 6 but with thicker (5-30 mm) beds, are also present.

Intraformational mudstone rip-up clasts, shell fragments, wood fragments, and mm-scale coaly fragments locally demarcate truncation surfaces, and less commonly, define lamination within the sandstone beds. In some instances, sand-sized coal fragments can constitute significant percentage of grains in the sandstone, inducing a "coffee ground" texture (Figures 3.15.A and 3.15.B). These beds are typically associated with large, intraformational mudstone rip-up clasts and organic-rich mudstones. Of particular note within these "coffee ground" sandstone beds, spherulitic siderite commonly demarcates lamination. The mudstone rip-up clasts present in Facies 7A are characteristically less than 1cm long, are angular to sub-angular, locally imbricated, and are commonly sideritized. The shell lags are most commonly composed of small (mm-scale) layers of calcareous shell hash, but locally are present as beds 3 cm to 10 cm thick. Interspersed with the sandstone beds are rare carbonaceous claystone drapes. These drapes range in thickness from 0.5 cm to 8 cm, are sharply bounded, commonly partially to fully sideritized, and display massive bedding. Minute, sand-filled synaeresis cracks are found subtending from the upper contact of the claystone beds. Large, sand-filled, scour and fill structures are present in some cores (Figure 3.15.C). Interbedded, current rippled sandstones and laminated, carbonaceous-rich mudstones exhibiting sandstone stringers are a unique feature seen in this facies (Figure 3.15.D). Micro-faulting is common within Facies 7A.

Ichnology:

The major portion of Facies 7A is essentially unbioturbated; however the top 5-15 cm of the laminated sandstone beds locally exhibit moderate degrees of bioturbation. Ichnogenera present in the low-angle and undulatory cross-laminated sandstones include *Ophiomorpha* (r), fugichnia (vr-m), *Skolithos* (vr), *Cylindrichnus* (vr-r), *Teichichnus* (vr-r), *Diplocraterion* (vr), *Palaeophycus* (vr-r), and *Rosselia* (vr). Low to moderate intensities of *Macaronichnus segregatis* (r) can be observed locally in association with the high-angle cross bedding and larger wave-ripple cross lamination. The carbonaceous claystones and mudstones are essentially unbioturbated, with the exception of localized *Planolites* (vr) and *Chondrites* (vr).

Interpretation:

The thickly bedded, laminated sandstones of Facies 7A are interpreted to reflect storm-influenced, proximal delta front deposition. This facies is characterized by low-angle planar parallel and wavy parallel lamination, interspersed with trough cross-stratified and current rippled sandstone. Trough cross-stratification becoming dominant towards the top. The aforementioned low-angle laminations are interpreted as SCS and HCS deposits reflecting storm wave reworking of the substrate. This shows two competing processes were active in the deposition of Facies 7A, those being episodic flood deposition, and fair-weather wave/storm wave reworking. The trough cross-stratified and current-rippled sandstones in the upper portions of Facies 7A can be indicative of current action, inferred to originate from close proximity to distributary channels. The abundant carbonaceous detritus demarcating stratification and lamination also imply influence of fluvial outflows. However, the thick sandstone beds exhibiting trough cross-stratification could also result from deposition in a high-energy surf zone. The dominant physical processes in this setting are wave-forced currents generating sinuous-crested subaqueous dunes (Pemberton, *et al.*, 2001). The unique occurrence of interbedded current rippled sandstone and laminated mudstone is interpreted to be the result of inertia-dominated hyperpycnal flow. These density-driven underflows are induced by the density contrasts between the sea water and the denser, sediment-laden waters of fluvial origin. Of note are the sandstone stringers within the carbonaceous mudstones indicating that in this instance, the mudstone was deposited by traction

Figure 3.13. Facies 7A:Thickly bedded, laminated sandstone.

Proximal Delta Front

A) Typical appearance of the laminated sandstones of the proximal delta front. This sample is characterized by low-angle tabular cross-stratification (?SCS). Note the *Macaronichnus segregatis* (Ma) and sub-vertical *Skolithos* (Sk). Well 16-12-73-11W6, depth 950.65m.

B) Mudstone rip-up clasts (sideritized in this example) are a common feature in the proximal delta front, often demarcating truncation surfaces and laminae. Low-angle tabular bedding is visible in the upper portion of this photograph. Well 07-25-75-10W6, 686.1m.

C) Small-scale trough cross-stratification transitioning to low-angle tabular bedding. Sideritized mud clasts are present at the base of the photograph, and are draped by parallel lamination. The dark color is due a high amount of macerated organic detritus collecting on laminations. Well 16-12-73-11W6, depth 950.95m.

D) Hummocky cross-stratified, upper very-fine grained sandstone. Ichnogenera present include *Palaeophycus* (Pa) and fugichnia (Esc). Well 11-33-71-12W6, depth 1232.3m.

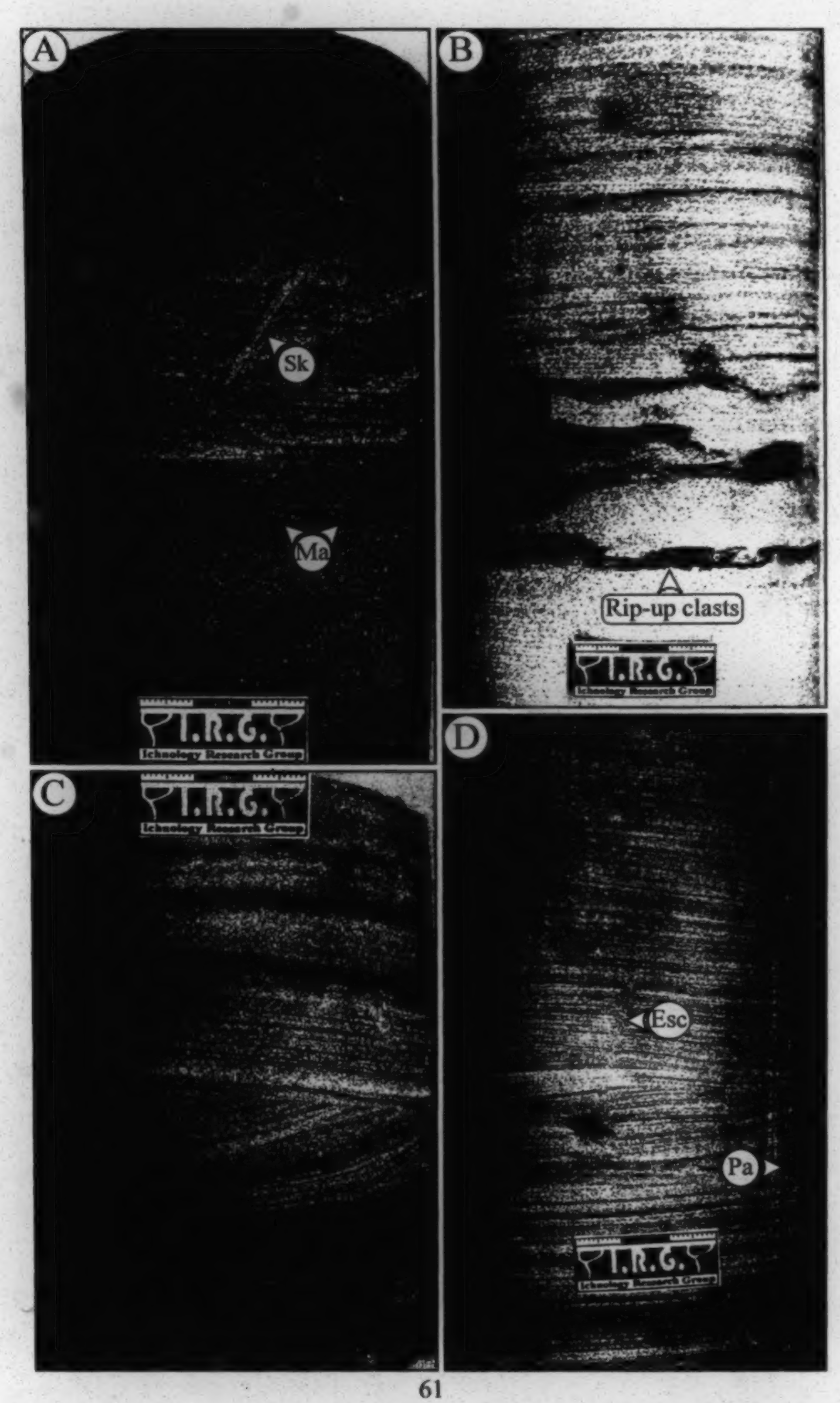
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Figure 3.14. Facies 7A:Thickly bedded, laminated sandstone.

Proximal Delta Front

A) Large-scale trough cross-stratification. Note the upward-increase in angle of the dipping beds corresponding to a toeset to foreset transition. Well 08-23-71-8W6, depth 1041.1m.

B) Low-angle planar bedding transitioning to small-scale hummocky cross-stratification. Well 14-34-74-10W6, depth 709.7m.

C) Low-angle tabular bedding (Planar tabular?) capped by aggradational combined-flow ripple cross-lamination. Well 16-29-74-9W6, depth 710.05m.

D) Example of swaley cross-stratification in Facies 7. Well 07-25-74-11W6, depth 836.48m.

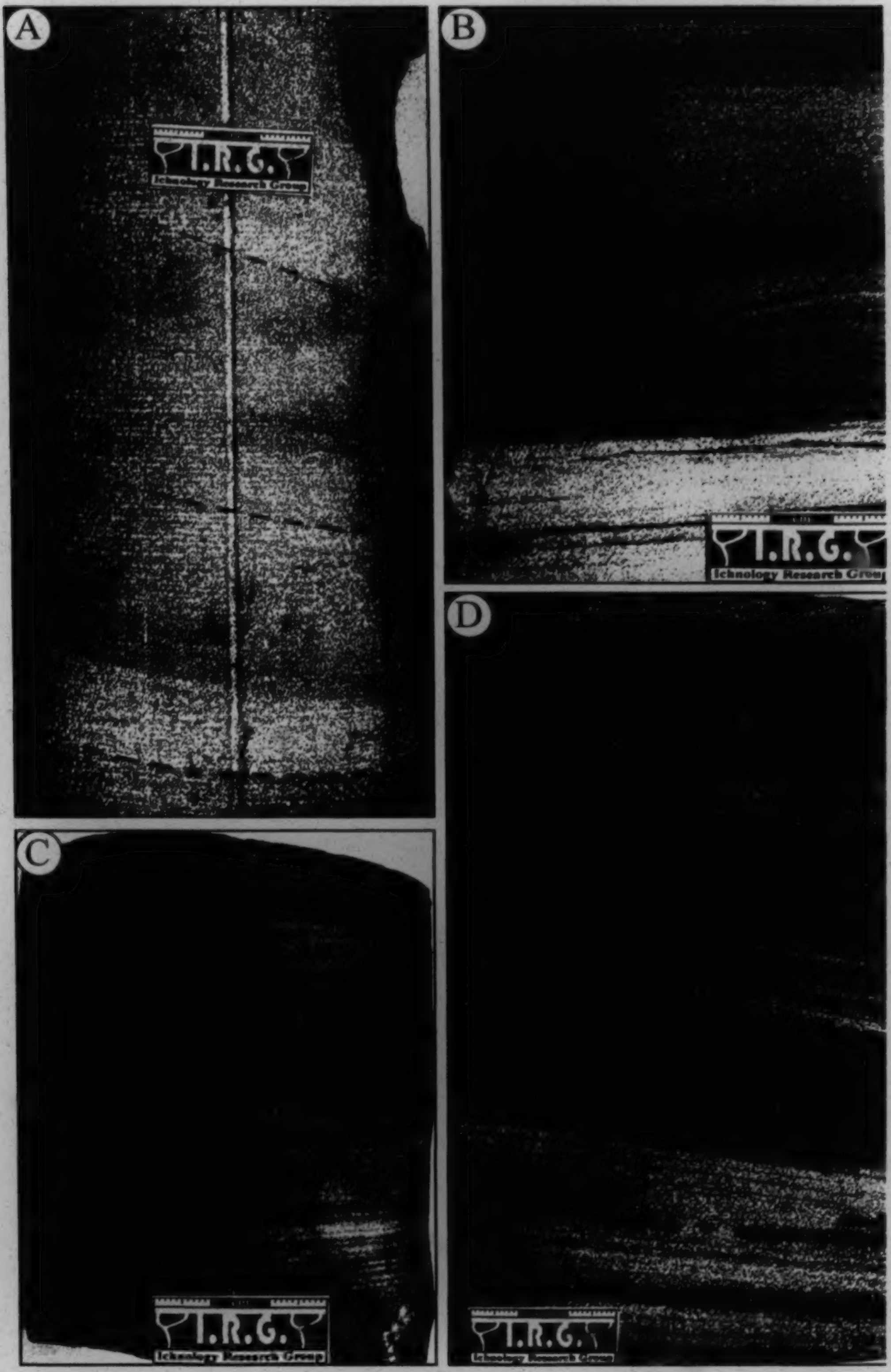
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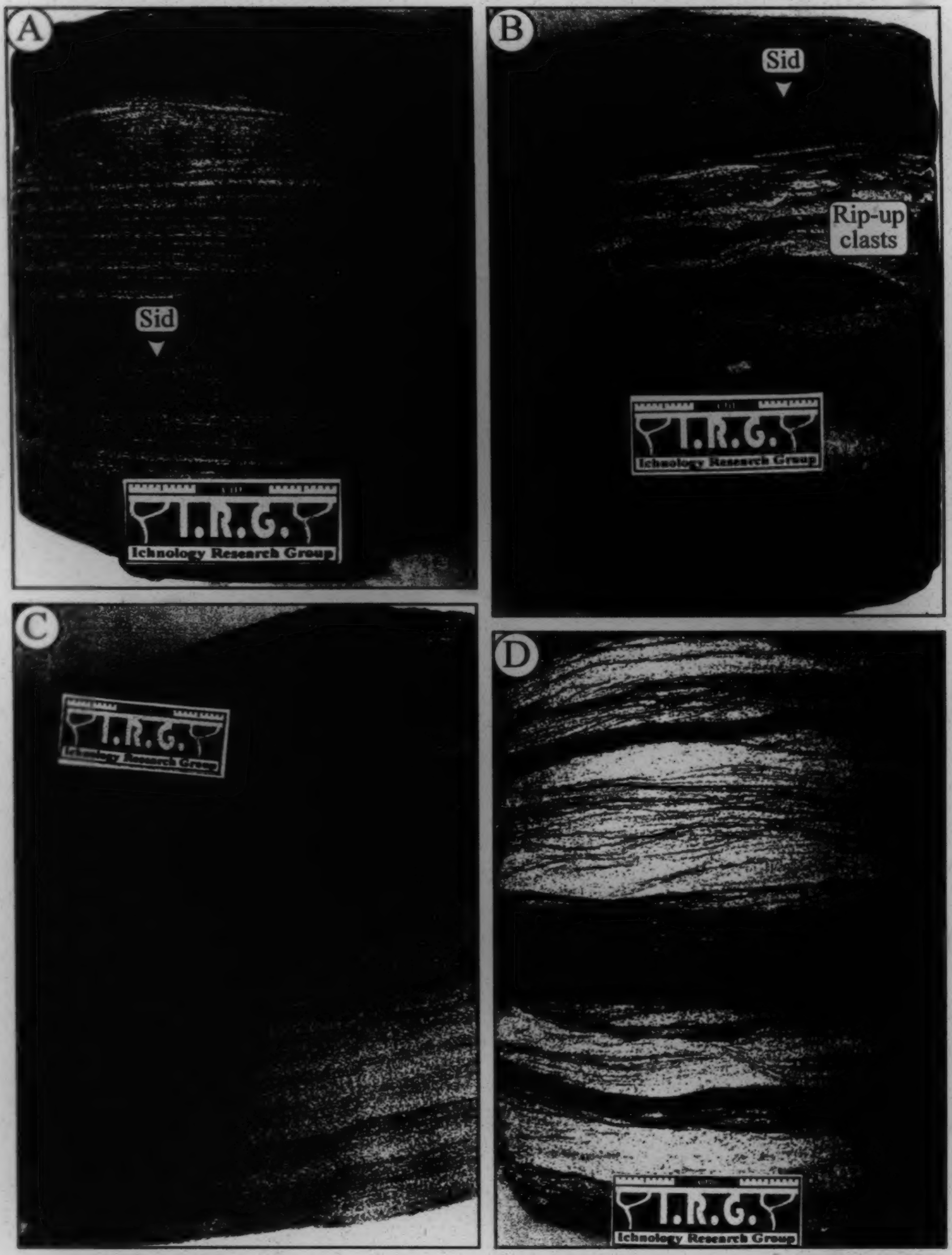
Figure 3.15. Facies 7A:Thickly bedded, laminated sandstone. Unique Features

Proximal Delta Front

A)-B) A moderately common feature in the delta front are beds containing abundant macerated organic detritus, sand sized coal clasts, and spherulitic siderite (Sid). This occurrence is significant, as these spheroids of siderite are actually detrital clasts sourced from paleosols, not mineralization features. Note the "coffee ground" texture of the laminae and partial sideritization of the large intraformational mudstone rip-up clasts. A) Well 16-35-74-9W6, depth 725.82m. B) Well 14-32-74-9W6, depth 698.8m.

C) Large sand filled gutter cast. Note the subtle inclined bedding within the gutter cast and en-echelon microfaulting in the subjacent beds which exhibit rythmic lamination interpreted as tidal couplets. Well 08-09-73-12W6, depth 1010.55m.

D) Typical appearance of inferred hyperpycnal flow deposits. Note the predominance of flasers and current ripple cross-lamination in the sandstone beds, and sandstone stringers in the parallel laminated mudstone beds. Well 06-09-73-10W6, depth 1000.5m.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currents, not via suspension fallout. The direct observation of an inertia-dominated hyperpycnal flow deposit is significant, as it clearly demonstrates fluvial influence on this facies.

The paucity of fine-grained material and dominance of wave-formed structures in the lower portions of Facies 7A is indicative of continuous reworking by waves. In contrast to Facies 6, the tempestites in Facies 7A show a high degree of erosional amalgamation, exhibiting only rare occurrences of preserved mudstone. This suggests a shallower environment of deposition subject to persistent wave agitation, induced by fair-weather and/or storm activity (Aigner and Reineck, 1982; MacEachern and Pemberton, 1992; Walker and Plint, 1992; Pemberton and MacEachern, 1997; Pemberton *et al.*, 2001). The presence of moderately bioturbated zones capping the HCS/SCS intervals is consistent with tempestite depositional models (*cf.* Howard and Frey 1984; Pemberton and Frey 1984; Pemberton and MacEachern 1997), representing fair-weather colonization of the substrate (Figure 3.15.D). The carbonaceous claystone and mudstone drapes that are preserved in Facies 7A reflect deposition from suspension during more quiescent or fair-weather conditions, accelerated by rapid flocculation of the fine-grained material. This flocculated material would in effect, mantle the underlying storm bed, possibly precluding colonization of the sand (Coates and MacEachern, 1999; MacEachern *et al.*, 2005). The synaeresis cracks seen in these muds are interpreted to reflect salinity variations, likely induced by density underflows of sediment-laden freshwater into the marine environment (Burst, 1965; Plummer and Gostin, 1981). The large sand-filled scour and fill structures (Figure 3.15.C) are interpreted as gutter casts (Whitaker, 1973). This particular structure is considerably larger than those seen in previous facies and may reflect sustained sand-rich, density underflow or the generation of a rip current. The spherulitic siderite present in the "coffee ground" sandstones beds is interpreted to originate from erosion of paleosols on the delta plain (Leckie *et al.*, 1989; Retallack, 1997).

Several factors contribute to the low bioturbation intensities seen in Facies 7A. Evidence of persistent storm events suggests an environment exhibiting periodically inhospitable hydraulic conditions as well as a possible taphonomic barrier to the preservation of fair-weather suites (see Figure 3.13.D). Other factors inhibiting faunal colonization include river flood events (often storm related) resulting in an inundation of both coarse and fine sediment; reduced salinities in areas proximal to distributary channels and periodic fluxes of fresh- and/or brackish-water via density underflows; unstable substrates due to high water content and relatively steep depositional gradients on the delta front, and increased water turbidity. The resultant ichnological suite represents a sporadically distributed, stressed expression of the mixed *Skolithos-Cruziana* ichnofacies. The notably low occurrence of suspension/filter-feeding traces, which typically dominate the *Skolithos* ichnofacies, is interpreted to be the result of high water turbidity in sediment-laden riverine outflows which inhibit these types of feeding strategies (Moslow and Pemberton 1988; Gingras *et al.* 1998; Coates and MacEachern 1999; MacEachern *et al.* 2005). The paucity of bioturbation in the carbonaceous claystones reflect anoxic conditions associated with the bacterial degradation of abundant incorporated organic material.

3.2.9 Facies 7B: Laminated to Structureless, Deformed Sandstone

Lithology and Sedimentary Features:

Facies 7B is relatively uncommon, occurring intercalated with, and/or locally capping, Facies 7A. It is typically between 0.5 m and 3 m thick (Figure 3.16). The facies is comprised predominantly of lower medium grained sand with less common silty, upper fine-grained sand. The most distinctive characteristics of this facies are soft sediment deformational features such as over-steepened bedding, convolute lamination, contorted bedding, ball and pillow structures, and microfaulting (Figure 3.16.A). Other features include visually structureless sandstones (Figure 3.16.B), weakly defined, low-angle planar parallel lamination (Figures 3.16.C and 3.16.D), and trough cross-stratification. The base of Facies 7B is typically sharp, and erosionally truncates underlying beds of Facies 7A. The deformed horizons commonly grade into sandstones exhibiting low-angle, planar parallel cross-bedding and large-scale trough cross-stratification. Wood fragments, sand-sized coal fragments, finely comminuted organic detritus, and intraformational rip-up clasts, which can be partially or fully sideritized, are ubiquitous.

Ichnology:

No trace fossils are observed in the deformed portion of this facies. Rare instances of *Macaronichnus segregatis* and diminutive *Ophiomorpha* (Figure 3.16.D) were recorded from the laminated and cross-bedded sandstones.

Interpretation:

This facies is characterized by three main sedimentological features, 1) Soft sediment deformed silty sandstones and sandstones; 2) apparently structureless sandstone; and 3) weakly defined, low angle, planar parallel laminated sandstone. Soft sediment deformation and structureless sandstones are the most enigmatic of sedimentary features, having several possible origins. The apparently structureless sandstones are interpreted to have formed by sediment liquefaction instigated by rapid expulsion of pore water due to abnormally high pore pressures. The associated convoluted laminations, contorted bedding, and ball and pillow structures are consistent with synsedimentary deformation related to rapid emplacement of material on a water-laden substrate. This rapid deposition of sand can be accounted for in two ways. The association of Facies 7B with Facies 7A, indicates that it was also deposited in a storm influenced, proximal delta front setting. This depositional environment would be subject to rapid deposition of sand via storm wave action (tempestites) as described in Facies 7A. If newly deposited sand was of sufficient thickness, and was emplaced on strata containing high pore water content, which is a common occurrence in deltaic settings (Reading and Collinson, 1996), rapid dewatering of the substrate will commonly take place. This dewatering process could result in homogenization of the substrate, obliterating any lamination present, as well as induce the observed convolute bedding and ball and pillow structures. Alternatively, there is evidence in Facies 7A of episodic, heavy fluvial discharge. During flood stages, fluvial systems tend to carry abundant sediment as bedload and suspended load. This can lead to density underflows of sediment-laden, riverine water (hyperpycnal discharge), which would instigate a form of turbidity current in which the structureless sands would be formed, roughly equivalent to the "A" bed of the Bouma Sequence (Bouma, 1963). A third possible explanation of the deformed and massive sandstones is mass movement and slumping of previously deposited material. Due to the nature of steep depositional profiles inherent to delta fronts, slumping of sediments is common (Coleman and Prior, 1982; Lindsay *et al.*, 1984). An important note about these massive and apparently structureless sandstones, if they are the result of rapid dewatering and substrate homogenization, is that sedimentary structures that may have been present are commonly destroyed. Another possible origin for the structureless sandstones is the effect of burrowing organisms. *Macaronichnus* has been shown to impart a high degree of homogenization of laminated upper shoreface and foreshore sandstones (Saunders and Pemberton, 1986; Saunders, 1989; Pemberton *et al.*, 2001). However, discreet *Macaronichnus segregatis* burrows were found only locally. Cryptically bioturbated sandstones have also been a proposed mechanism of "structureless" sandstones (Saunders *et al.*, 1994; Pemberton *et al.*, 2001). In this scenario the action of meiofauna (organisms ranging from 0.1 mm to 1mm that live within the sediment) tend to disturb lamination. This results in "fuzzy" laminations, or potentially complete homogenization of the substrate. However, in upper fine-sand and larger grain sizes, the action of meiofauna is limited as the pore spaces and pore throats can be of sufficient size that they can move

Figure 3.16. Facies 7B: Laminated to Structureless, Deformed Sandstone.

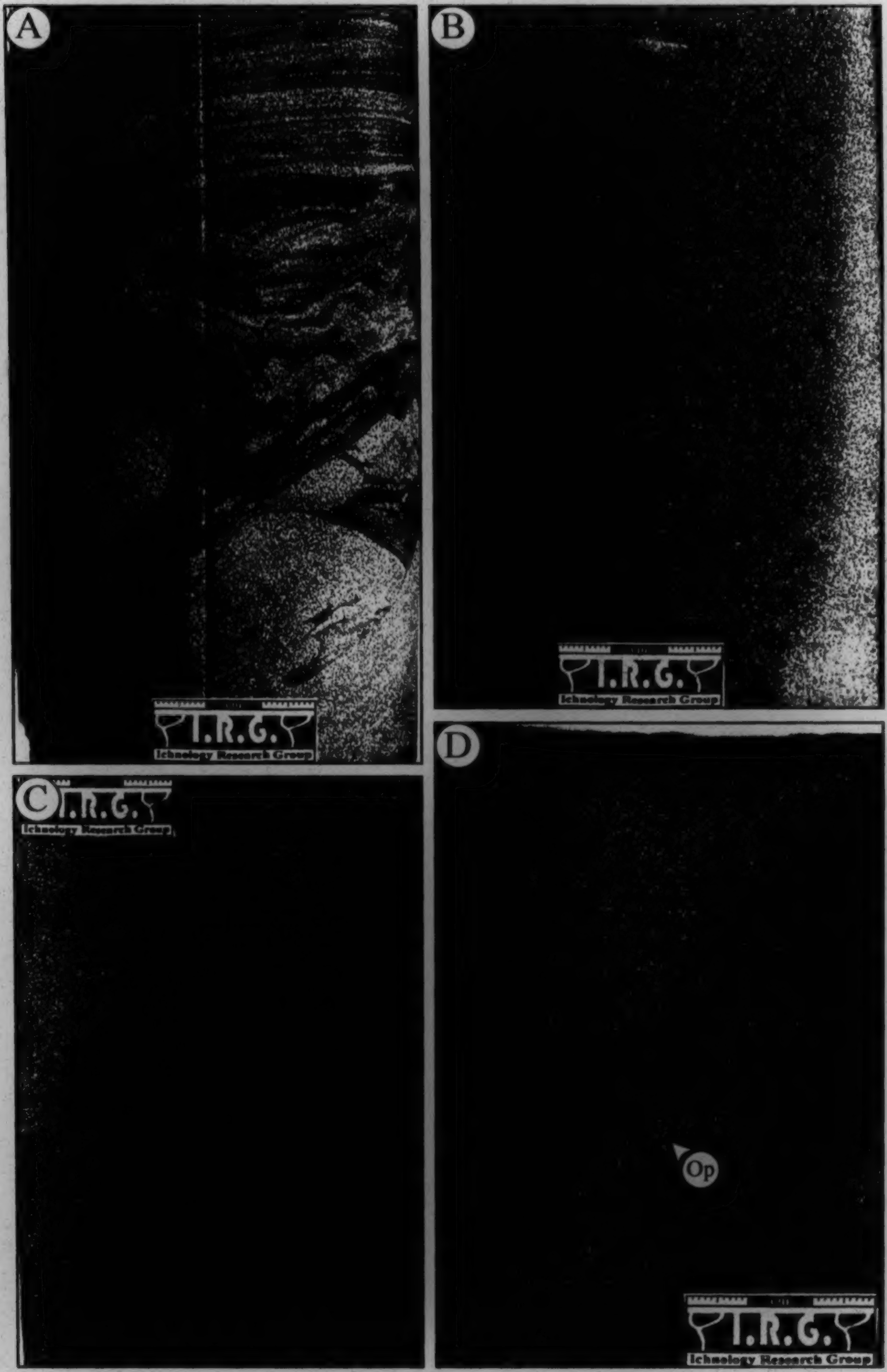
Distributary Mouth Bar

A) Convoluted silty sandstone erosionally truncated by low-angle planar parallel laminated silty sandstone. Well 07-26-74-9W6, depth 758.75 m.

B) Structureless sandstone, a common occurrence in Facies 7B. Slight grain size variations from lower medium-grained to upper fine-grained sand indicate possible, near-horizontal planar parallel bedding. Well 06-07-75-11W6, depth 800.05 m.

C) Lower medium-grained sandstone exhibiting extremely diffuse, low-angle planar parallel lamination (planar tabular?), truncation surface outline with dashed line. Well 14-35-74-10W6, depth 700.1 m.

D) Low angle planar parallel bedded sandstone. Note the diminutive *Ophiomorpha* (Op). Well 14-34-74-10W6, depth 706.32 m.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about freely, without "jostling" sediment.

The weakly defined, low-angle, planar parallel bedding is also difficult to characterize in terms of a single depositional process. Similar lamination patterns are observed in Facies 7A and in the thicker sandstone beds of Facies 6, and are interpreted to represent SCS. However, that interpretation was facilitated by observations of laminations exhibiting an upward decrease in lamination angle, responding to the filling of swales, and the association of other oberved wave-formed or wave-influenced features such as oscillation ripples, combined-flow ripples, and HCS. The lack of such evidence in Facies 7B suggests that the low-angle, planar parallel bedding was not deposited as a result of storm-induced wave activity. There are two probable mechanisms for the development of the bedding seen in Facies 7B. The low-angle planar parallel bedding may reflect swash-zone stratification deposited in a foreshore environment. Alternatively, this bedding pattern could have resulted from a unidirectional current characterized by upper flow regime planar bedding (Harms, *et al.*, 1982). The observation of *Macaronichnus segregatis* within the laminated sandstones is consistent with swash-zone deposition (Saunders and Pemberton, 1986; Saunders, 1989; Pemberton *et al.*, 2001). However, *Macaronichnus* was found only locally, indicating that the foreshore interpretation may have limited viability. This fact is compounded by the observations that Facies 7B is only distributed locally. If a well-developed swash-zone was present, it should be a more pervasive unit. The fact that Facies 7B is spatially restricted, occurring in localized, closely-spaced areas, implies an environment that is also spatially restricted such as a distributary mouth bar. Distributary mouth bars occur at river mouths, where seaward flowing water leaves the confines of the channel, spreading and mixing with the ambient waters of the receiving basin (Coleman and Prior, 1982). The effect on the river effluent of mixing with basinal water processes such as waves and tides is to decrease its transporting competency, leading to rapid deposition. Due to the rapid deposition inherent in mouth bar environments, coupled with progradation of mouth bar sands over previously deposited, water laden sediments of the delta front and prodelta, soft sediment deformation and slumping are common occurrences.

The severely restricted ichnological assemblage observed in Facies 7B is consistent with an inhospitable environment such as a distributary mouth bar, or episodic events such as tempestites or river flood discharges. It is this author's belief that all the aforementioned processes were likely to have been partly responsible for the features seen in facies 7B. In instances when Facies 7B is intercalated with Facies 7A, it is likely that episodic events such as storms or river floods were the cause. In instances when Facies 7B caps Facies 7A, it is likely that it represents the progradation of a distributary mouth bar complex over proximal delta front sandstones.

3.2.10 Facies 8: Interbedded, bioturbated sandstone and laminated sandstone

Lithology and Sedimentary Features:

Facies 8 typically grades out of the pervasively bioturbated muddy sandstones of Facies 3 and is characterized by intensely bioturbated muddy sandstone (Figures 3.17. and 3.18.). Due to the high degree of biogenic reworking, the majority of primary sedimentary structures are unidentifiable. Discrete sandstone beds are uncommon, but where observed are comprised of sharp-based intervals of laminated, upper very fine- to lower fine-grained sandstone beds. The laminated sandstone beds are typically 3-15 cm thick, and contain low-angle, undulatory parallel lamination, which grade into combined-flow ripples and/or wave ripple cross-lamination locally. Facies 8 can exhibit patchy to complete calcite cementation, as well as siderite mineralization and cementation.

Ichnology:

Bioturbation intensities range from moderate to high and ichnological diversity is high. The laminated sandstone beds tend to be bioturbated to a lesser degree but display an upward increase in the degree of reworking within the beds. Most of the ichnogenera are uniformly distributed throughout the facies. The trace fossil suite is dominated by inferred deposit feeders and mobile carnivores including *Ophiomorpha* (c-a), *Planolites* (m), *Rosselia* (m), *Rhizocorallium* (m-c), *Teichichnus* (c), *Siphonichnus* (m), *Cylindrichnus* (r-m), *Asterosoma* (r-m), and *Schaubcylindrichnus* (r). Common, but ancillary elements of the suite include grazing and foraging traces such as *Zoophycos* (r-m), *Scolicia* (r-m), *Helminthopsis* (c-a), and *Phycosiphon* (c). Less common trace fossils include *Diplocraterion* (r-m), *Skolithos* (m), *Conichnus* (vr), fugichnia (r-m), and bivalve equilibrichnia (r).

Interpretation:

The bioturbated sandstones of Facies 8 are interpreted to represent deposition at or near fair-weather wave base. These fair-weather deposits are punctuated by the sharp-based low-angle, wavy laminated sandstones interpreted as hummocky cross-stratified tempestites. The general absence of preserved lamination in the sandstones is a reflection of higher bioturbation intensities present in Facies 8 in comparison to Facies 6 and Facies 7A. The ichnological assemblage present in Facies 8 is characterized by a diverse and robust assemblage of deposit feeding structures complemented by a significant amount

Figure 3.17. Facies 8: Interbedded bioturbated muddy sandstone and laminated sandstone.

Lower Shoreface

A) Typical appearance of the lower shoreface. Note the moderate to high bioturbation intensities including a suite dominated by *Ophiomorpha* (Op) and *Rosselia* (Ro). This well exhibits significant calcite cementation and iron mineralization of burrow linings/mud accumulations. Well 08-26-75-11W6, depth 749.5m.

B) Highly bioturbated sandstone. Complex cross-cutting relationships make ichnogenera identification tenuous, however examples of *Ophiomorpha* (Op), *Teichichnus* (Te), and *Helminthopsis* (He) are evident. Well 06-13-76-11W6, depth 677.8m.

C)-D) Examples of *Ophiomorpha* (Op) and *Rosselia* (Ro) in plan view (C) and section view (D). Note the lateral migration of the Rosselia burrows noticeable in plan view. Well 11-33-71-12W6, 1234.83m.

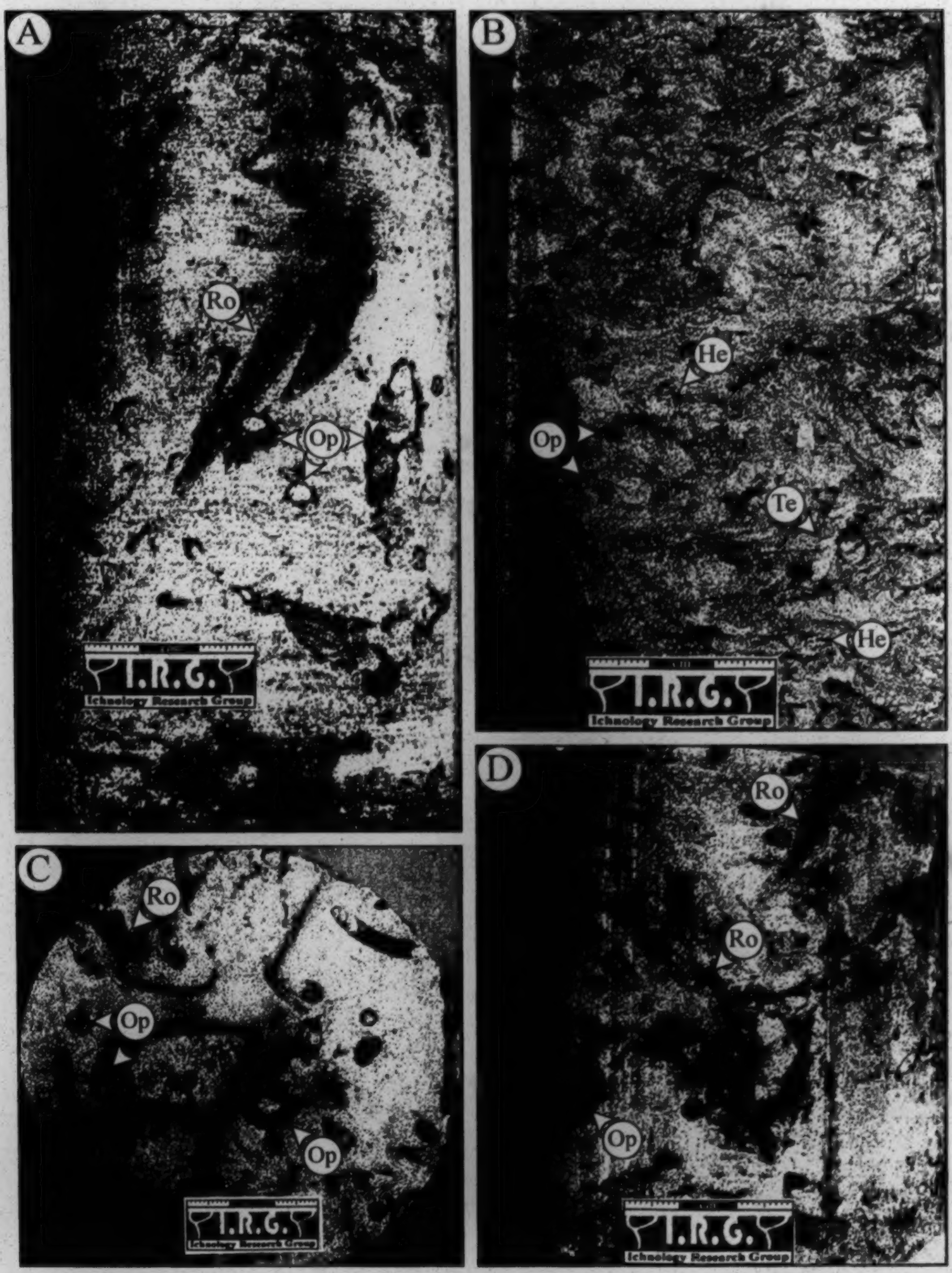
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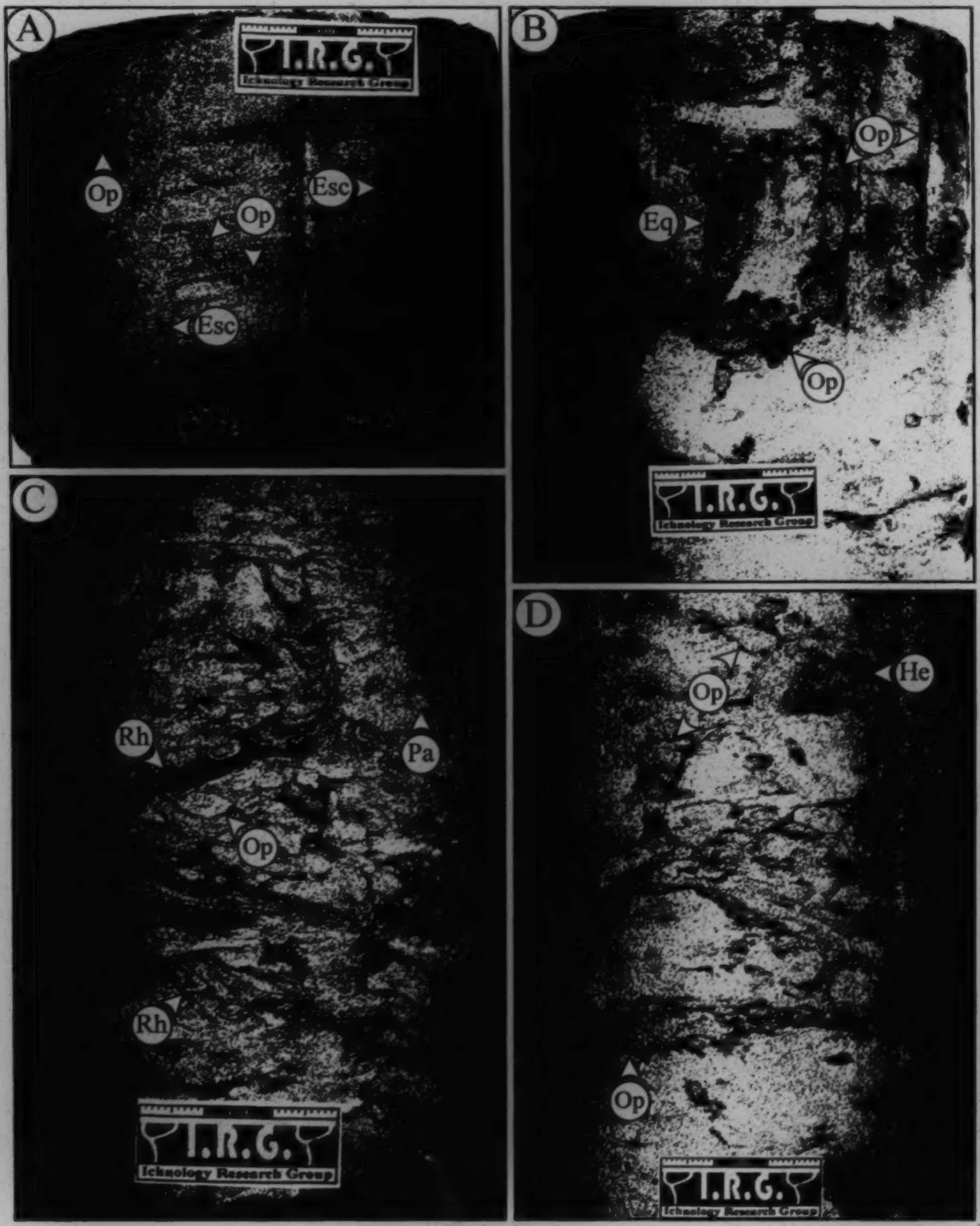
Figure 3.18. Facies 8: Interbedded bioturbated muddy sandstone and laminated sandstone.

Lower Shoreface

A) Typical appearance of the laminated sandstones associated with lower offshore deposits of the Doe Creek Member. Note the low-angle (<10°), parallel lamination (HCS?) and low to moderate bioturbation intensities. *Ophiomorpha* (Op) and vertical fugichnia (Esc) are present. Well 11-33-71-12W6, depth 1236.2m.

B)-D) Examples of ichnogenera common to the lower shoreface in the Doe Creek Member including *Ophiomorpha* (Op), *Rhizocorallium* (Rh), *Palaeophycus* (Pa), *Helminthopsis* (He), and bivalve equilibrichnia (Eq). B) Well 11-33-71-12W6, depth 1235.8m. C) Well 14-35-74-10W6, depth 712.05m. D) 11-33-71-12W6, depth 1236.1m.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suspended and re-suspended food particles persisting in the water column (*i.e.* fair-weather wave base). The observed assemblage is indicative of the proximal expression of the *Cruziana* ichnofacies (Pemberton *et al.*, 2001). Sedimentological and ichnological features of Facies 8 are similar to those observed in inferred "moderately storm-dominated" shorefaces (intermediate energy) of other sandstone units in the Cretaceous western interior (MacEachern and Pemberton, 1992). Facies 8 is therefore interpreted to represent the deposits of an open-marine, moderately storm influenced lower shoreface setting.

3.2.11 Facies 9: Moderately bioturbated, laminated sandstone

Lithology and Sedimentary Features:

Facies 9 is characterized by laminated sandstones and is distinguishable from Facies 7A by an increase in bioturbation intensity and ichnotaxa diversity. Facies 9 gradationally overlies Facies 8 for the most part, but it is locally found sharply overlying Facies 3, 4, or 5. The sandstone is dominantly upper very fine- and lower fine-grained sand. Low-angle planar parallel lamination and low-angle wavy parallel lamination are visible with rare occurrences of trough cross-stratification in the upper portions of the facies (Figure 3.19). Beds range in thickness from 5 cm to 35 cm, are typically sharp-based and grade upwards into combined-flow ripple cross-lamination and oscillation ripple cross-lamination which were observed locally. Carbonaceous mud drapes, common in the deltaic facies (Facies 4, 5, 6, and 7), are exceedingly rare and are typically only a few mm thick. Intraformational rip-up clasts occur locally on laminae and bedding planes, but are typically rare. The rip-up clasts present in Facies 9 are predominantly diminutive, rounded to sub-rounded pellets of fine grained material, in contrast to the large, angular mudstone rip-up clasts of Facies 7A and 7B. Facies 9 displays moderate amounts of patchy calcite cementation though it is locally pervasively cemented.

Ichnology:

The bioturbation intensity is typically low to moderate with many intervals remaining unbioturbated. The most common trace fossils are *Ophiomorpha* (m-c), *Palaeophycus* (m), *Skolithos* (m), *Conichnus* (r) and fugichnia (r-m), with locally abundant *Macaronichnus segregatis* (r-c) (Fig. 3.19.E). Subordinate elements of the ichnological suite include *Cylindrichnus* (r), *Diplocraterion* (r), and *Arenicolites* (vr-r), *Teichichnus* (r) and *Rosselia* (vr).

Figure 3.19. Facies 9: Moderately bioturbated sandstone.

Middle-Upper Shoreface

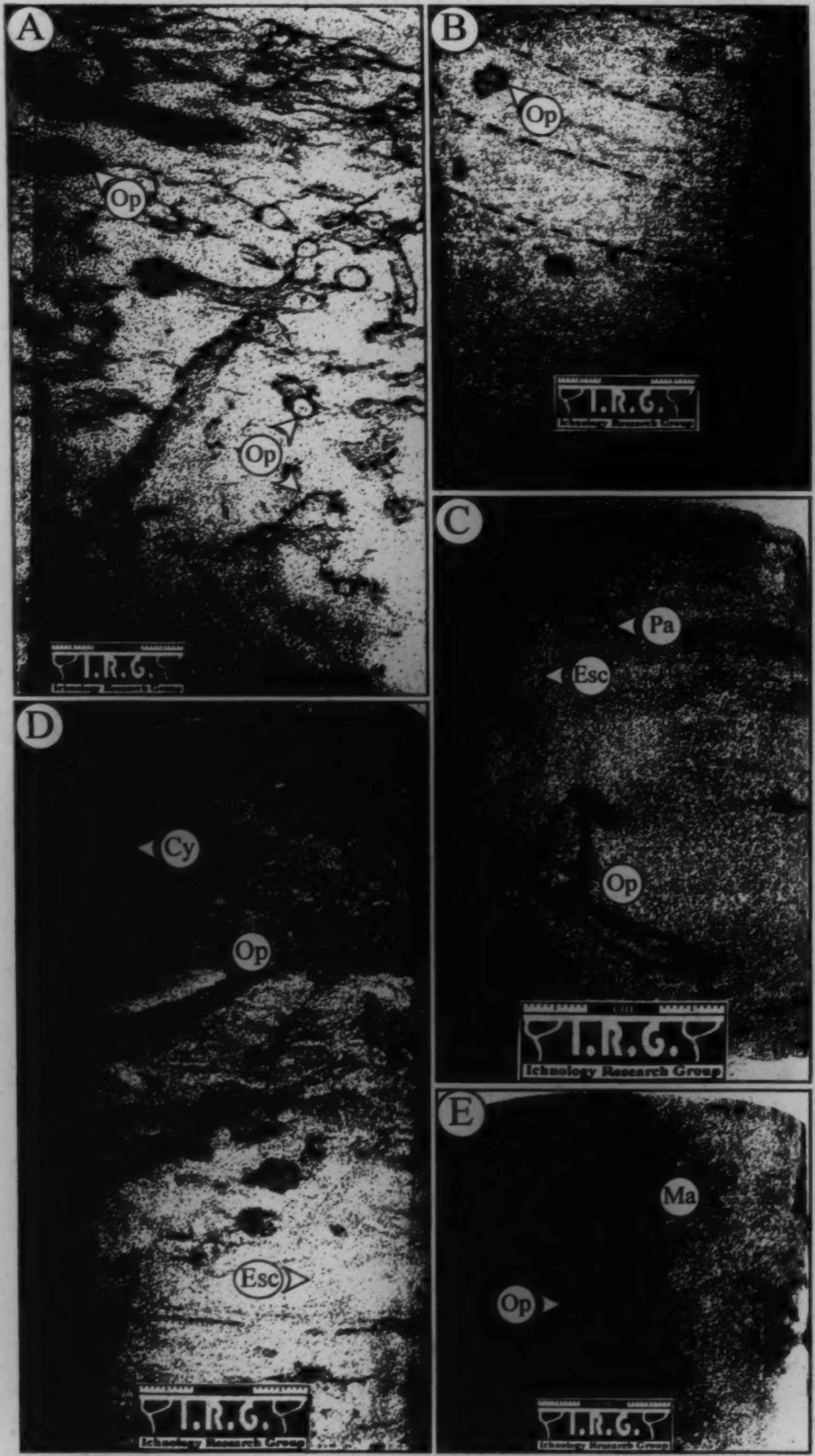
A) Moderately burrowed sandstone. Note the abundant *Ophiomorpha* (Op) and an indistinct, meniscate backfill structure (*Ophiomorpha irregulaire*). Well 06-03-73-8W6, depth 882.53m.

B) Typical appearance of the middle to upper shoreface deposits. Note the upward increase dip angle of bedding interpreted as trough cross-stratification. Ichnogenera present include *Ophiomorpha* (Op). Well 08-30-75-11W6, depth 835.85m.

C) A large, heavily pelleted *Ophiomorpha* (Op) accompanied by *Palaeophycus* (Pa) and fugichnia. Note the diffuse nature of the micaceous laminae indicating the possible influence of cryptic bioturbation (*cf.* Pemberton *et al.*, 2001). Well 14-31-74-10W6, depth 754.8m.

D) An example of the rare occurrence of a bioturbated interval capping SCS/HCS sandstones. Ichnogenera include Ophiomorpha (Op) and ?*Cylindrichnus* (Cy). Small fugichnia traces (Esc) can be seen in the laminated portion of the sandstone bed. Well 16-12-73-11W6, depth 750.12m.

E) Moderately burrowed sandstone. Note the predominance of *Macaronichnus segregatis* (Ma) and *Ophiomorpha* (Op). Well 11-33-71-12W6, depth 1234.35m.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Interpretation:

The sedimentary structures and features of Facies 9 reflect deposition in a high-energy, wave-dominated environment. The low-angle planar parallel and low-angle wavy parallel laminations are typical of amalgamated HCS and SCS beds. The thick beds of trough cross-stratified sandstone are characteristic of deposition in an upper shoreface setting (Davidson-Arnott and Greenwood, 1976; MacEachern and Pemberton, 1992; Pemberton *et al.*, 2001). The paucity of muddy interbeds is also suggestive of deposition above fair-weather wave base. The trace fossil suite is characterized by moderate diversities and bioturbation intensities, dominated by dwelling structures of inferred suspension feeders and passive carnivores, typical of the open-marine, archetypal *Skolithos* ichnofacies (MacEachern and Pemberton, 1992; Pemberton *et al.*, 2001). The sand-prone nature and predominance of physical sedimentary structures in Facies 9, coupled with an ichnological suite typical of the *Skolithos* ichnofacies, suggest deposition in a middle to upper shoreface environment.

3.2.12 Facies 10: Large-scale, cross-bedded sandstone

Lithology and Sedimentary Features:

Facies 10 has a distinct erosive base commonly demarcated by intraformational mudstone rip-up clasts. The sandstones are moderately sorted, varying from upper fine to lower medium-grain sand (Figure 3.20). Trough cross-stratification, low-angle planar lamination, and current ripple lamination are predominant. Other structures include rare aggradational current ripples, and apparently structureless beds. Carbonaceous detritus is ubiquitous and typically highlights lamination. In some cases, lamination exhibits a rhythmic character with possible couplets (Figure 3.20.B). Intraformational mudstone rip-up clasts are common, and range from several millimeters to 5 cm in length. These rip-up clasts are commonly concentrated into stringers along erosional truncation surfaces or laminae, but also occur dispersed within the massive sandstones with no apparent preferred orientation (Figure 3.20.D). Rare, 3-30 mm thick organic-rich mudstone partings are present and are very similar sedimentologically and lithologically to the mudstone rip-up clasts (Figure 3.20.C). Sand-sized coal debris and wood fragments are common throughout, but are typically associated with the erosional truncation surfaces. Soft-sediment deformation features such as contorted bedding and flame structures are locally associated with the mudstone partings. Facies 10 is relatively uncommon, and laterally discontinuous.

Ichnology:

Bioturbation intensities in Facies 10 are extremely low with rare *Ophiomorpha* (vr) dispersed throughout the sandstone. Rare mudstone partings contain small *Planolites* and *Thalassinoides* (Figure 3.30.E). A *Glossifungites* ichnofacies demarcated surface is locally developed at the base of Facies 10, consistent with an erosive contact. This is best expressed in well 06-35-75-10W6, where pebble and coarse-sand filled firmground *Thalassinoides* subtend into sandy mudstones of facies 3. Structures within the sandstones, such as "fuzzy" lamination suggest possible cryptic bioturbation (*cf.* Pemberton *et al.* 2001). *Macaronichnus segregatis* is sparsely distributed within the facies.

Interpretation:

The laminated sandstones of Facies 10 consistently display a sharp base, locally associated with a basal lag and/or *Glossifungites* ichnofacies, indicative of a highly erosive surface. The dominance of trough cross-stratification intercalated with unidirectional, current-generated structures and a lack of wave-formed structures support indicate a channelized environment. The mudstone rip-up clasts are typically large and angular indicating relatively short travel distances or low degrees of reworking. Mudstone rip-up clasts occurring without preferential orientation in a massive sandstone are unique to Facies 10. This is interpreted to have originated from very rapid deposition during bank collapse, where no equilibrium bedforms are developed. The carbonaceous mudstone beds indicate periods of quiescence, inferred to reflect waning flow after flood events (Reading and Collinson, 1996). During these lower energy periods, flocculated mud may be deposited from suspension fallout, collecting in localized depressions or in the troughs of bedforms. The presence of possible mud couplets and a sparse marine ichnological suite indicates an influx of marine water and possible tidal modification of bed forms, consistent with a lower delta plain distributary channel (Reading and Collinson, 1996). The extremely sparse ichnological suite of *Planolites* and rare *Thalassinoides* are interpreted to represent the burrowing behavior of trophic generalists, a common feature in stressed, brackish settings (Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; MacEachern *et al.*, 1999a; Gingras *et al.*, 1999; Pemberton *et al.*, 2001).

Figure 3.20: Facies 10: Large-scale, cross-bedded sandstone.

Distributary Channel

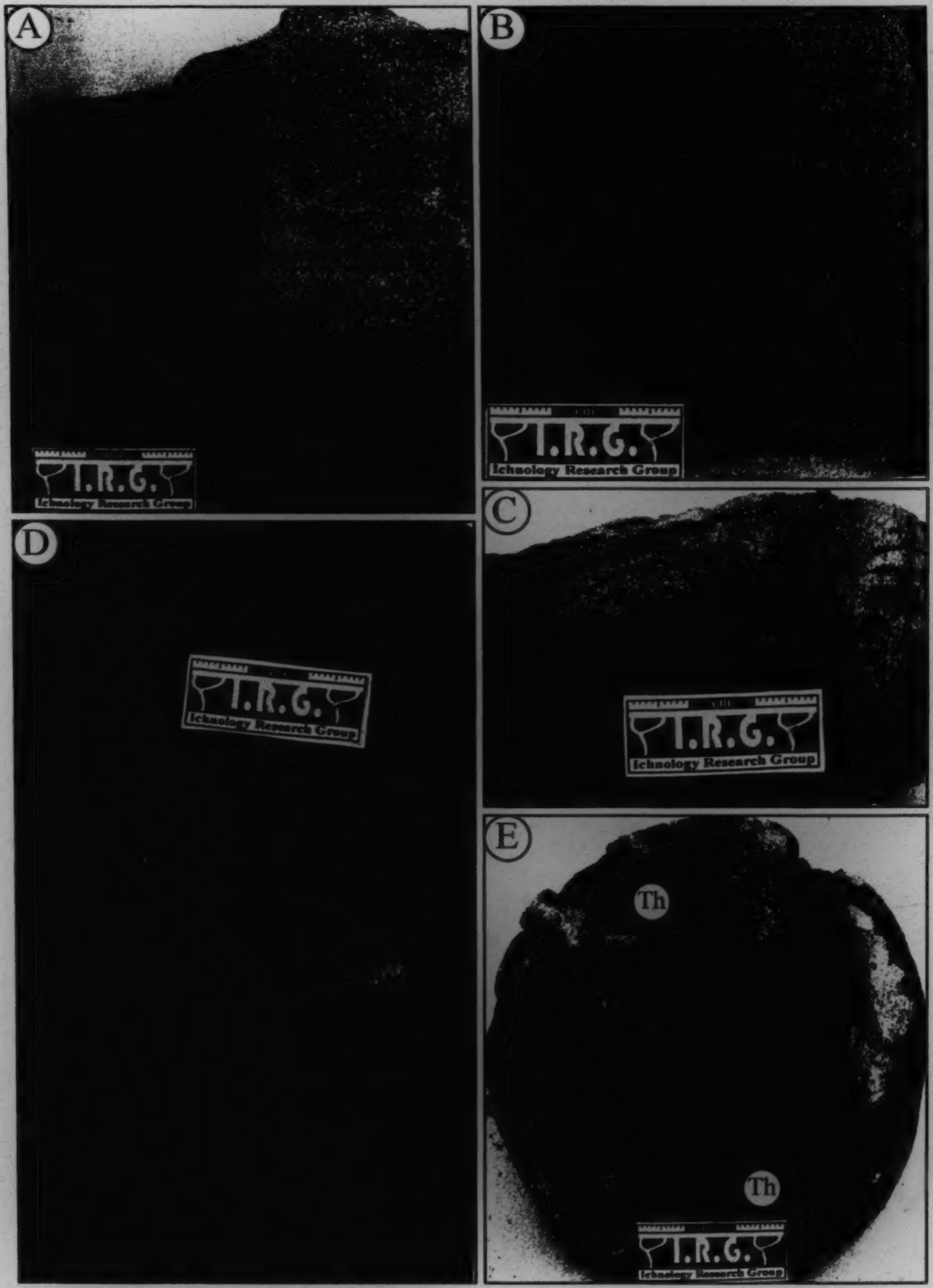
A) Typical appearance of distributary channel deposits in the Doe Creek Member. Note the current ripple cross-laminated beds in the upper portion of the picture. The extremely diffuse character of the laminae suggests rapid deposition or possible influence of cryptic bioturbation. Well 08-10-75-12W6, depth 793.5m.

B) Low-angle tabular bedding displaying possible tidally induced, double mud drapes. Laminae display possible influence of cryptic bioturbation. Well 06-25-75-10W6, 708.7m.

C) Organic-rich mud drapes are a familiar occurrence in Doe Creek Member distributary channel deposits. Note the irregularity of the drapes indicating soft-sediment deformation. The flame structure apparent in the lower left indicates rapid emplacement of the superjacent sandstone. Well 02-13-76-10W6, depth 690.25m.

D) Large, extremely angular intraformational mudstone clasts supported in a massive sandstone matrix. This particular example is interpreted to be a bank-collapse deposit. Well 06-25-75-10W6, depth 705.15m.

E) A solitary occurrence of *Thalassinoides* (Th) within the Doe Creek Member distributary channel deposits. This is a bottom-up view of *Thalassinoides* in an organic-rich mudstone bed which has disintegrated over time revealing the burrows. Well 06-25-75-10W6. 710.1m.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Ichnology Research Group

3.2.13 Facies 11: Sparsely bioturbated mudstone

Lithology and Sedimentary Features:

This facies comprises black, carbonaceous mudstones and shales delicately interbedded with thin (<5 mm) laminae of lower very fine-grained sandstone (Figure 3.31). The proportion of shale and mud varies from 80-95%, but locally drops to 50 percent. Very little structure is observed in the mudstones, which commonly appear massive with weakly developed lamination. The sandstone beds characteristically display sharp and/or loaded bases, with individual beds commonly discontinuous across the width of the core. The sandstone beds locally include oscillation ripples, current ripples, and wavy parallel lamination. The lamination style is often difficult to discern due to the thinness of the bed and predominance of soft-sediment deformation. The most common forms of soft-sediment deformation in Facies 11 are contorted bedding, dewatering structures, and load-cast ripples. Carbonaceous detritus, synaeresis cracks, siderite nodules, and sideritized beds are common. Facies 11 is limited in occurrence and is rarely correlatable.

Ichnology:

The bioturbation intensity ranges from barren to very low (Figures 3.31.A and 3.31.B). The ubiquitous nature of the soft-sediment deformation makes trace fossil identification tenuous at best. *Planolites* (vr) is the most common ichnogenus that can be seen in Facies 11. Other trace fossils present include *Teichichnus* (vr), *Palaeophycus* (vr) and *Chondrites* (vr). Facies 11 is commonly overlain by Facies 3 or 4, and burrows locally penetrate into Facies 11 from above. These burrows should not be mistakenly attributed to Facies 11.

Interpretation:

Facies 11 displays the most restricted and impoverished trace fossil suites of the fine-grained facies in the Doe Creek Member. The fine-grained character, coupled with the predominance of simple biogenic structures formed by trophic generalists and low diversities are consistent with deposition in a low-energy brackish-water environment (Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; MacEachern *et al.*, 1999a; Gingras *et al.*, 1999; Pemberton *et al.*, 2001). Brackish water ichnological assemblages are characterized by: (1) lower diversity, (3) diminutive marine forms (3) simple structures constructed by trophic generalists, (4) domination by a single ichnogenus, and (5) vertical and horizontal trace fossils common

Figure 3.21. Facies 11: Sparsely bioturbated mudstone

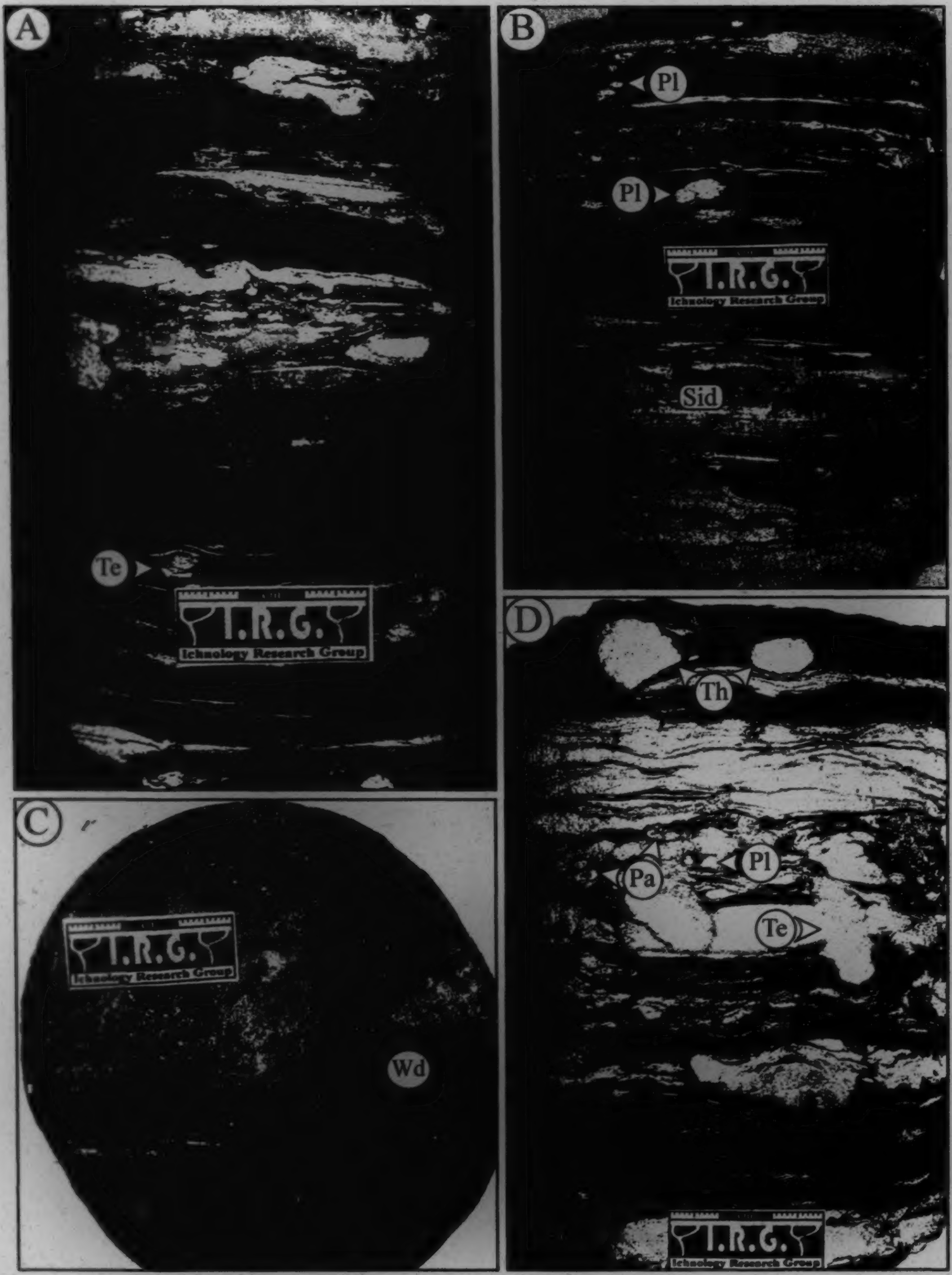
Brackish Bay Deposits

A) Typical appearance of brackish bay deposits in the Doe Creek Member. The bay deposits are characterized by organic-rich, laminated mudstones displaying extremely low bioturbation intensities. Note the abundant deformation, predominantly load-cast features, in the sandstone beds. A diminutive ?*Teichichnus* (Te) is the only trace fossil present. Well 14-24-75-10W6, depth 709.95m.

B) Sideritized horizons are common features of the bay deposits. Note the sparse *Planolites* (Pl). Well 08-35-76-8W6, depth 569.6m.

C) Large wood fragments (Wd) and macerated coal fragments are commonly found on bedding planes. Well 11-04-75-9W6, depth 713.7m.

D) This is an example of the highest bioturbation intensities and diversities found in the Doe Creek Member bay deposits. These localized sand-rich zones in the bay deposits are characterized by slightly more diverse and intense bioturbation. Ichnogenera present include *Thalassinoides* (Th), *Palaeophycus* (Pa), *Planolites* (Pl), and *Teichichnus* (Te). Well 08-35-76-8W6, depth 568.95m.


A
Te
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B
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Pl
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Sid
C
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Wd
D
Th
Pa
Pl
Te
I.R.G.
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domination by a single ichnogenus, and (5) vertical and horizontal trace fossils common to both the *Skolithos* and *Cruziana* ichnofacies. There are several possible interpretations of this facies, based on observed vertical facies relationships. Facies 11 commonly overlies distributary channel sandstones of Facies 10. This relationship could be the result of avulsion and abandonment of distributary channels, leading to stagnant, quiet-water conditions. Facies 11 is also recognized to overlie Facies 7A. This scenario can be explained through simple progradation, as brackish-water interdistributary bay sediment is deposited over previously deposited delta-front sandstones. Delta lobe abandonment or transgression commonly leads to the development of barrier island systems as the delta front is reworked by waves (Penland *et al.*, 1985, 1988). This process can lead to the formation of low energy, brackish-water back-barrier lagoon environments. Facies 11 is also consistent with deposits of a delta-margin bay or lagoon setting.

3.3 FACIES ASSOCIATIONS

Facies Associations are defined as, "…groups of facies that occur together and are considered to be genetically or environmentally related" (Reading, 1986). Doe Creek Member of the study area consists of two distinct end member facies associations, each comprising a vertical succession of genetically related deposits. Facies Association 1 (FA1) corresponds to deltaic accumulation and Facies Association 2 (FA2), reflecting open-marine shoreface deposition. FA1 consists of fully marine shelf and offshore deposits, overlain by a deltaic complex. A typical facies succession includes 1) shelf shales and distal offshore mudstones (F1A and F1B), 2) varying amounts of open-marine offshore deposits (F2 and F3) depending upon the degree of deltaic influence reaching the offshore, 3) prodeltaic deposits (F4 and F5), passing into 4) delta front sandstones (F7A, F7B), and locally capped by 5) interdistributary bay/lagoon deposits (F11).

FA2 consists of 1) shelf and distal offshore deposits (F1A and F1B), followed by 2) offshore deposits (F2 and F3), overlain by 3) shoreface sandstones (F8 and F9). Both facies associations are locally interrupted by the presence of distributary channels (F10) and/or bay fills (F11). FA1 and FA2 appear virtually identical on well-logs, though the distributary channel deposits typically have a distinctive, sharp-based, blocky appearance on gamma-ray logs. It is important to note that FA1 and FA2 represent end-members in a spectrum of facies successions. Deltaic and open-marine shoreface successions are commonly deposited penecontemporaneously on a given shoreline, and thus display a gradational and interfingering relationship, along depositional strike.

CHAPTER 4

STRATIGRAPHIC AND DEPOSITIONAL MODEL

4.1 INTRODUCTION

The previous chapter described the eleven facies identified in this study and discussed their associated interpretations. This chapter broadens the scope of investigation placing the individual facies into spatial context to allow for the development of a depositional model of the Doe Creek Member. The nature and origin of the highly productive sandstones found within the Doe Creek Member are of particular interest for hyrdocarbon exploration and exploitation. The facies analysis completed on cored intervals of the Doe Creek Member demonstrate a dichotomy of depositional systems was prevalent along the paleo-shorelines during deposition. FA1 comprised a succession of deposits consistent with that of a prograding, open-marine shoreface system, whereas FA2 was deposited as a result of the progradation of a deltaic coast. Several geologic maps and cross-sections are presented to elucidate the relationships of the facies and facies associations present in the Doe Creek Member. Utilizing the geologic data obtained from the facies analysis, isopach maps, and stratigraphic cross-sections, a depositional model is proposed linking facies associations and explaining the emplacement of the Doe Creek Sandstone bodies.

4.2 MAPS

The Doe Creek Member is characterized by a series of stacked parasequences, which are defined as conformable successions of genetically related beds and bedsets that are bounded by flooding surfaces and their correlative conformities (Van Wagoner *et al.*, 1988). Flooding surfaces separate younger strata from older strata across which there is evidence of an abrupt increase in water depth. Plint (2000) separated the Lower Kaskapau Formation into two units, a basal unit comprising strata from the top of the Dunvegan formation to the Doe Creek "X" marker, and an upper unit bounded by the Doe Creek "X" marker below and the Doe Creek K1 marker above. The stacked parasequences comprising the lower Kaskapau Formation are by and large comprised of shales, mudstones, and siltstones of inner-shelf and offshore origin. Within the X-K1 interval of Plint (2000), the Doe Creek Member contains well developed sandstones which are productive hydrocarbon-bearing units within the study area. Two of these are developed into large mappable bodies. These sandstone bodies are informally named the Doe Creek "I" and "A" sandstones in ascending stratigraphic order (ERCB, 1986; Wallace-Dudley and Leckie, 1988, 1993, 1995). These two sandstones were mapped utilizing a seventy percent sandstone/shale cutoff on gamma ray logs, which was calibrated from core data as being "clean" sand.

The Doe Creek "I" sandstone (Figure 4.1) exhibits an elongate shape oriented northeast-southwest paralleling the paleo-shorelines of the underlying Dunvegan Formation (Bhattacharya 1991b, 1993; Wallace-Dudley and Leckie, 1993; Plint, 2000). There is a distinct lobate form in the main sandstone body centered in township 72-11W6. The sandstone becomes progressively thinner to the northeast, and appears to continue to the southwest beyond the boundaries of the study area. Also of note is the smaller isopach thick centered in township 78-8W6. The morphology of the sandstone is consistent with that of a wave-influenced delta front sandstone body (Coleman and Wright, 1975; Galloway, 1975; Bhattacharya and Walker, 1992; Bhattacharya and Giosan, 2003). The Doe Creek "A" sandstone is a more linear feature than the Doe Creek "I" and is oriented approximately north-south (Figure 4.2). The Doe Creek "A" also exhibits a subtle lobate form centered in township 74-11W6 and a secondary isopach thick in township 78-11W6. The change is orientation between the two sandstones can be attributed to either changes in sedimentation rate and accommodation filling or tectonic modification of basin morphology or a combination of both. Regional drainage patterns for both the Dunvegan Formation and Doe Creek Member were from the northwest to the southeast paralleling the cordilleran thrust belt. The prevalent shoreline trends were northeast-southwest, orthogonal to the thrust belt. If the rate of subsidence caused by tectonic loading in the thrust belt increased faster than the sedimentation rate could fill the accommodation space, or if a there was a drop in sedimentation rate, shorelines would tend to become parallel to the cordilleran front. Chen and Bergman (1999) proposed that differential subsidence of the tectonic domains of the Alberta basement played a major role in the depositional centers and shoreline orientations in the Dunvegan and Doe Creek intervals.

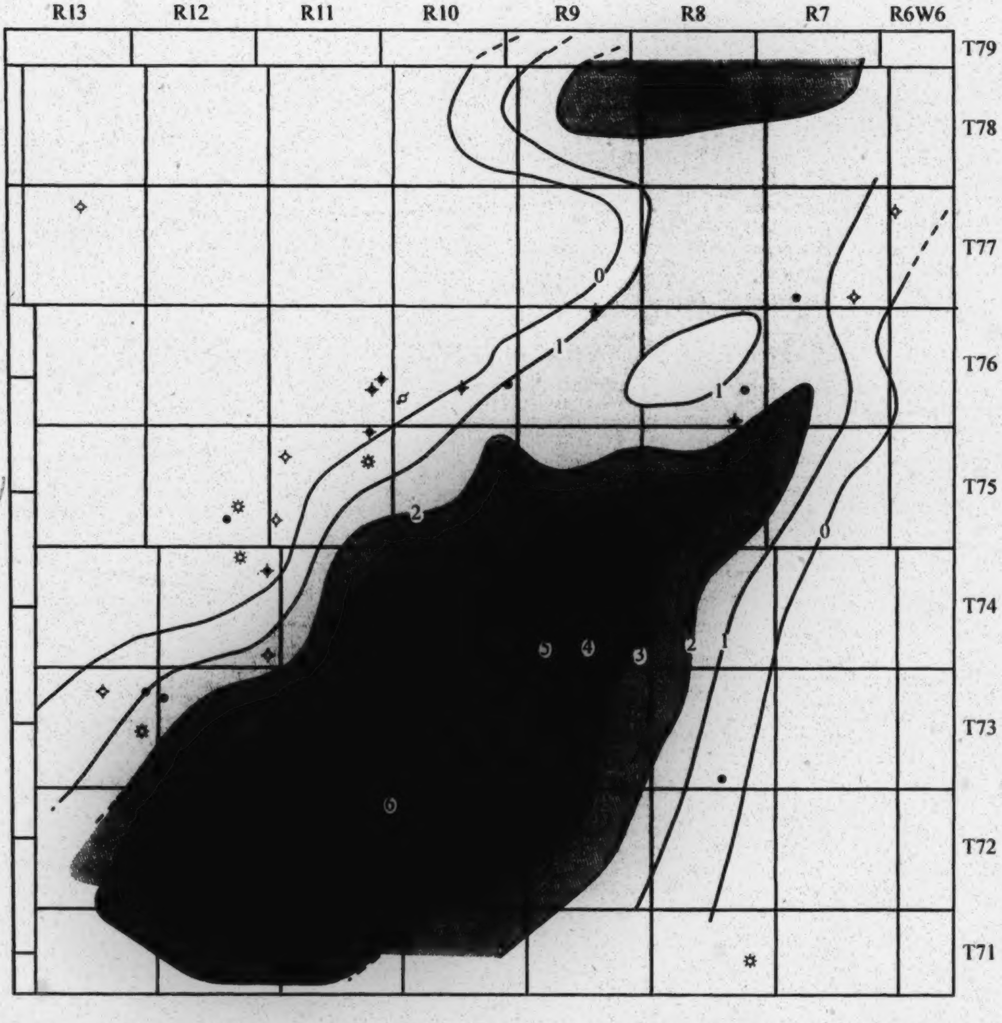

R13
R12
R11
R10
R9
R8
R7
R6W6
T79
T78
T77
T76
T75
T74
T73
T72
T71
0
1
2
1
6
5
4
3
2
1
0

Figure 4.1. Net sand isopach of the Doe Creek "I" sandstone. Net sand values were obtained using a 70% "clean sand" gamma ray cutoff. Contour interval: 1m

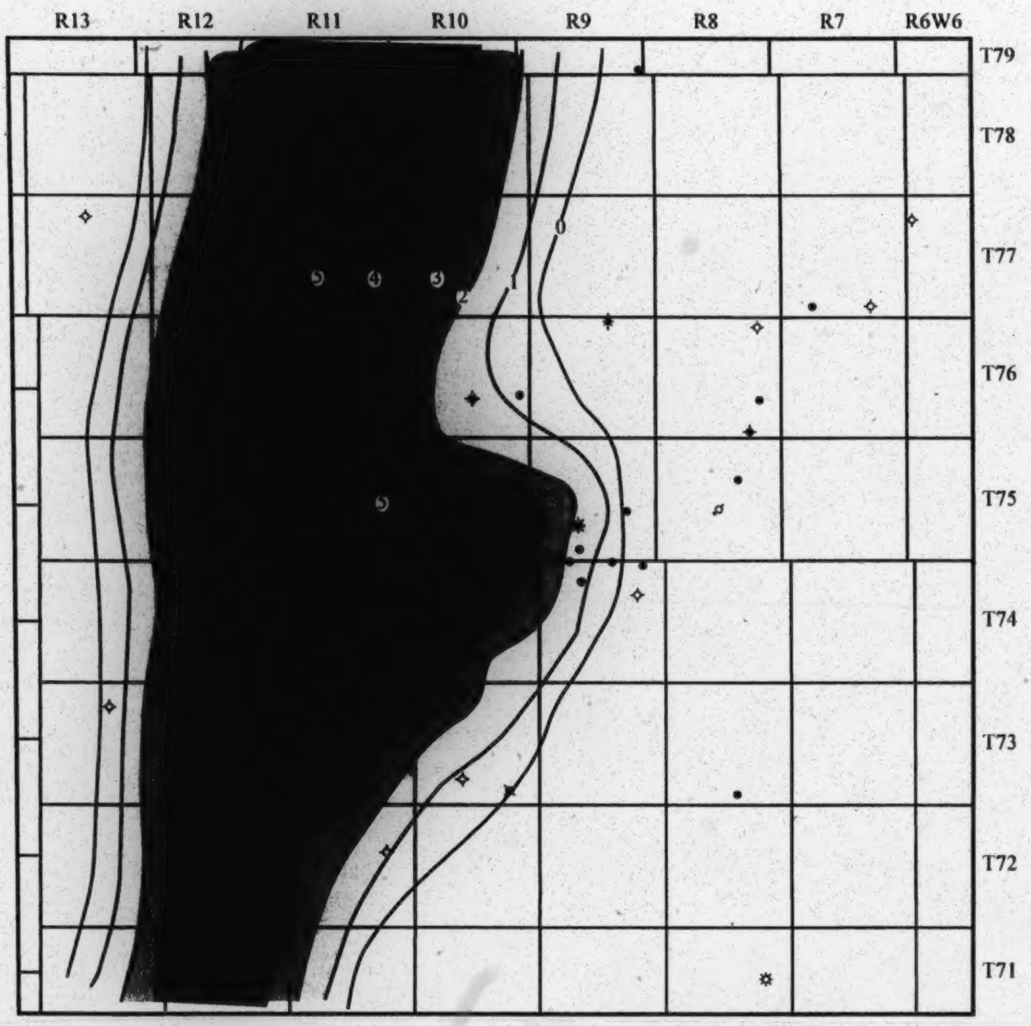

R13
R12
R11
R10
R9
R8
R7
R6W6
T79
T78
T77
T76
T75
T74
T73
T72
T71
0
1
2
5
4
3
5

Figure 4.2. Net sand isopach of the Doe Creek "A" sandstone. Net sand values were obtained using a 70% "clean sand" gamma ray cutoff. Contour interval: 1m

4.3 CROSS SECTIONS

In order to elucidate the nature of the depositional architecture and evolution of the Doe Creek Member, three key cross sections were constructed in the study area see Figure 1.1B for locations). The wells selected for the cross sections contain cored intervals through the Doe Creek Member facilitating an evaluation of the facies architecture. Each cross section is presented using the gamma ray log from the well log suite as well as the lithologs generated from the core description. The datum used is a regional flooding surface observed throughout the study area (DCM1) that occurs between 20 to 30 meters above the Doe Creek sandstones. The litholog sections are hung on flooding surfaces capping the sandstones for ease of illustration.

Cross section A-A' is oriented parallel to depositional dip, and shows the two main shoreline sandstone bodies, Doe Creek "I" and Doe Creek "A", in the central part of Valhalla Field (Figure 4.3). The stratigraphically lower shoreline trend, Doe Creek "I", is the predominant hydrocarbon producer. The base of the Second White Speckled Shale (SWSS), interpreted as a maximum flooding surface, occurs approximately 50-75 m above the DCM1 across the study area. However, due to post-Doe Creek structural influences on the overlying Kaskapau Formation shale, the base of the SWSS is not a reliable datum. The DCM1 surface was chosen based on its conspicuous and widespread occurrence across the study area, providing an adequate datum. However, this surface can impose aberrant stratigraphic artifacts on the cross sections which will be discussed in a later section.

The most prominent feature in this cross section is the basal discontinuity (BD2). BD2 occurs as a distinct *Glossifungites* ichnofacies-demarcated surface at the base of the distributary channel in well 06-25-75-10W6. BD2 demarcates the sharp base of the Doe Creek "I" sandstone in the central wells of the cross section, but becomes a gradational contact, inferred as the correlative conformity, in a down-dip direction as shown in well 07-26-74-9W6. The top of the Doe Creek "I" sandstone is discriminated by a sharp increase in radioactivity on gamma-ray logs indicating a abrupt shift from clean sandstone to shale or mudstone, interpreted as a flooding surface (FS3). BD2 shows an apparent stratigraphic rise in well log cross-section A-A' (Figure 4.3 and core cross-section A-A' (Figure 4.4) to the southeast (i.e. basinward). This is not a primary stratigraphic relationship, but is in fact related to the nature of the datum used. Both erosional and depositional marine markers dip gently seaward. When these markers are used as horizontal datums, they tend to distort stratigraphic markers and relationships (see MacEachern *et al.* 1998).

The core cross section (Figure 4.4) accompanying the well log section focuses on the Doe Creek "I" sandstone, and is hung on FS3 for ease of representation. The erosive nature of BD2 is clearly discernible, as it cross cuts offshore deposits (F2 and F3) and prodelta deposits (F4) (see well 11-09-75-9W6). Sharp-based shorefaces have been variously interpreted to be the result of late highstand deposits, forced regressive systems, lowstand systems, or transgressively incised deposits (see MacEachern *et al.,* 1999b; Pemberton *et al.,* 2004). With the exception of highstand shorefaces, each of these scenarios results in an erosive, sharp-based shoreface body which can be sedimentologically identical and thus indistinguishable. The distinction between sharp-based shorefaces is dependant on the characteristics of the basal and upper bounding surfaces (MacEachern *et al*., 1999b; Pemberton *et al*., 2004). Lowstand shorefaces are bounded by a lowstand surface of erosion (LSE) and its correlative conformity below, and a flooding surface/ravinement surface above. A forced regressive shoreface is bounded by a regressive surface of erosion (RSE) below, and a flooding surface sequence boundary (FS/SB) above. A transgressively incised shoreface is bounded at the base by an FS/SB. Lowstand shorefaces lie directly on sequence boundaries and their correlative conformities, and represent the basinward limit of shoreface progradation within a single sequence (Plint 1988; Posamentier et al. 1992). Forced regressive shorefaces also have a sharp basal discontinuity (the regressive surface of erosion or RSE), but the correlative conformities of RSE have very low preservation potential as continued progradation and eventual lowstand shoreface incision tends to remove some of the forced regressive deposits (MacEachern et al. 1999b). Transgressively incised shorefaces can be distinguished by the presence of the transgressive ravinement occurring seaward of the basinward limit of fair-weather wave base during subsequent progradation (MacEachern *et al*. 1999b). BD2 can be best interpreted as LSE (sequence boundary), and the Doe Creek "I" sandstone is interpreted as a lowstand incised shoreface due to the preserved correlative conformity seaward of BD2.

In well 11-09-75-9W6, a facies transition (FT1) demarcates a conformable facies transition from fully marine offshore F3 and prodeltaic F4 deposits. This upper surface of F4 is truncated by BD2 in a basinward direction, and is overlain by the same flooding surface (FS3) that caps the main Doe Creek "I" sandstone. FT1 is interpreted to represent the basinward shift of facies accompanying base-level fall during the falling stage. BD2/FS3 is interpreted as an amalgamated flooding surface sequence boundary. The down-dip transition from a sharp-based shoreface to a conformable and gradational succession is clearly evident between wells 16-29-74-9W6 and 07-26-74-9W6. As BD2 contact is followed in a basinward direction it becomes a conformable succession of fully marine

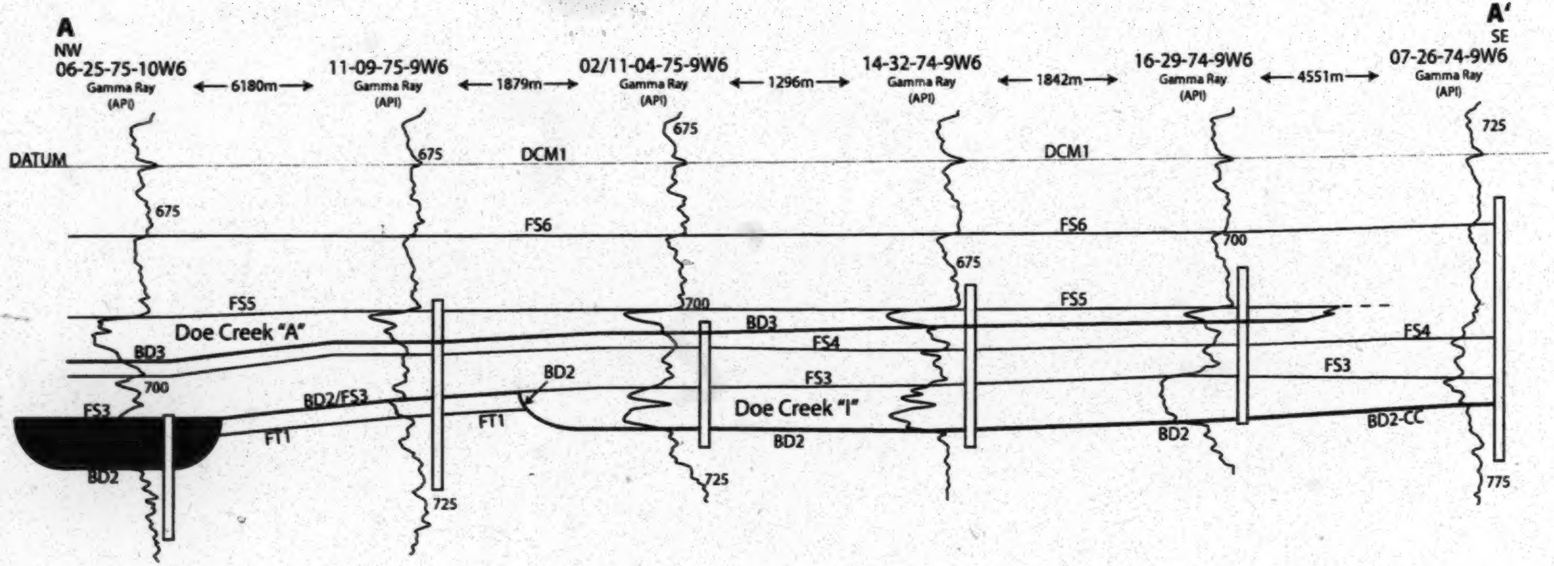

A
NW
06-25-75-10W6
Gamma Ray (API)
6180m
11-09-75-9W6
Gamma Ray (API)
1879m
02/11-04-75-9W6
Gamma Ray (API)
1296m
14-32-74-9W6
Gamma Ray (API)
1842m
16-29-74-9W6
Gamma Ray (API)
4551m
A'
SE
07-26-74-9W6
Gamma Ray (API)
DATUM
DCM1
DCM1
675
675
675
675
675
700
700
700
700
725
725
725
725
775
FS6
FS6
FS5
FS5
Doe Creek "A"
BD3
BD3
FS4
FS4
FS3
FS3
FS3
BD2
BD2/FS3
BD2
FT1
FT1
Doe Creek "I"
BD2
BD2
BD2-CC

Figure 4.3. Well-log cross section A-A'. See Figure 1.1B for locations. Red line demarcates lowstand surface. Shaded boxes indicate cored intervals.

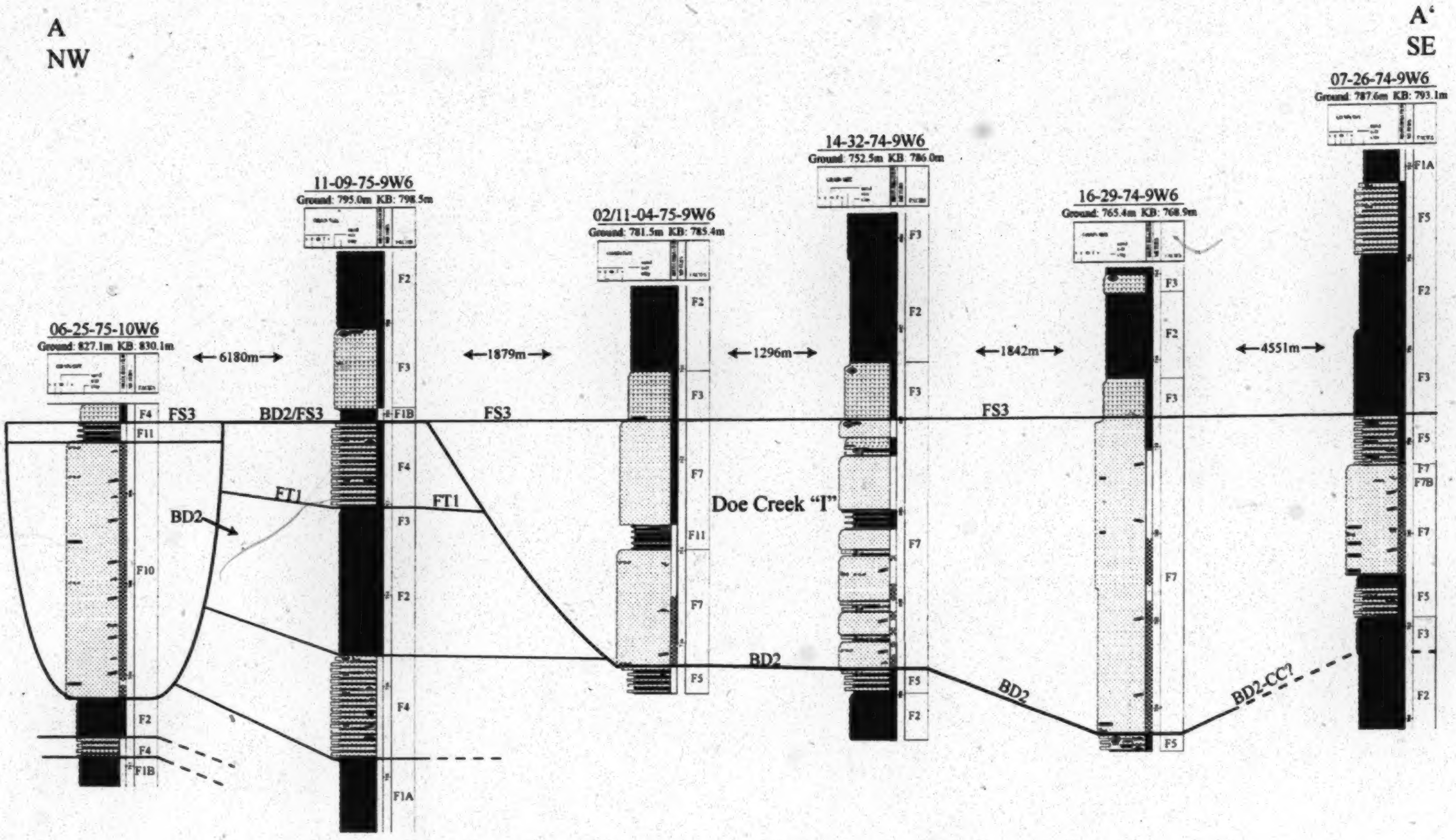

A
NW
A'
SE
06-25-75-10W6
Ground: 827.1m KB: 830.1m
11-09-75-9W6
Ground: 795.0m KB: 798.5m
02/11-04-75-9W6
Ground: 781.5m KB: 785.4m
14-32-74-9W6
Ground: 752.5m KB: 786.0m
16-29-74-9W6
Ground: 765.4m KB: 768.9m
07-26-74-9W6
Ground: 787.6m KB: 793.1m
←6180m→
←1879m→
←1296m→
←1842m→
←4551m→
FS3
BD2/FS3
FS3
FS3
FT1
FT1
BD2
BD2
BD2
BD2-CC?
Doe Creek "I"
F4
F11
F10
F2
F4
F1B
F2
F3
F1B
F4
F3
F2
F4
F1A
F2
F3
F7
F11
F7
F5
F3
F2
F3
F7
F5
F2
F3
F2
F3
F7
F5
F1A
F5
F2
F3
F5
F7
F7B
F7
F5
F3
F2

Figure 4.4. Core cross section A-A'. See Figure 1.1B for locations. Red line demarcates lowstand surface.

offshore (F2 and F3) to deltaic deposits (F5 and F7).

Cross section B-B' is oriented parallel to the depositional strike of the Doe Creek "I" sandstone and uses DCM1 as the datum (Figure 4.5). The apparent dip is induced by the basin asymmetry caused by tectonic loading in the Cordillera, and should be disregarded for this stratigraphic and depositional investigation. The sandstone-prone facies of the Doe Creek "I" regressive cycle is persistent along depositional strike, but exhibits a highly variable character on well logs and core. FS1 and FS2 are surfaces bounding minor shelf-to-offshore regressive packages. The BD2 surface shows a great deal of variability across the base of the sandstone package, indicating that the erosive nature of BD2 is also variable along depositional strike. BD2 is an abrupt, sharp contact in the southwest, consistent with the sharp-based nature of the Doe Creek "I" lowstand shoreface, but becomes progressively gradational in the northeast, associated with thinner sandstones.

The accompanying core cross section B-B' (Figure 4.6) clearly shows the drastic shoreline parallel variability of BD2 and the Doe Creek "I" sandstone. The core cross section is hung on FS3 for ease of illustration. As one moves along the Doe Creek "I" sandstone from the southwest to the northeast, two distinctive changes occur: 1) the delta-front sandstones of F7 (the main reservoir facies) thins drastically; and 2) the succession becomes gradational, whereby delta front processes cannibalize prodelta and distal delta front deposits to a lesser degree during base-level fall. This is somewhat analogous to the sharp-based to gradational relationship seen in dip-oriented cross-sections of the Doe Creek "I" sandstone. The lateral variation in character of BD2 is interpreted to have been induced by proximity to a riverine point source. The up-dip association of distributary channels with well 14-32-74-9W6 and the increase in thickness of the delta-front deposits indicates that the point source for the Doe Creek "I" sand was located toward the southwestern end of cross section B-B'. The implications of this along-shore variability are twofold: 1) higher reservoir potential and quality are associated with close proximity of point sources on delta-influenced shorelines in the Doe Creek Member; and 2) the character of the basal discontinuity of sharp-based shorelines can change significantly along depositional strike. Additionally, the "sharpness" of a sharp-based shoreline can be facies dependant, and therefore can be limited in areal extent.

An interesting vertical facies relationship occurs in well 08-35-76-8W6, where slightly more than one meter of brackish bay/lagoon (F11) deposits are intercalated with proximal prodelta (F5) and distal delta front. This occurrence of Facies 11 may have resulted from distributary abandonment, interdistributary bay deposition, or they could be deposits of a delta margin bay. The gamma ray signature in well 01-35-76-8W6

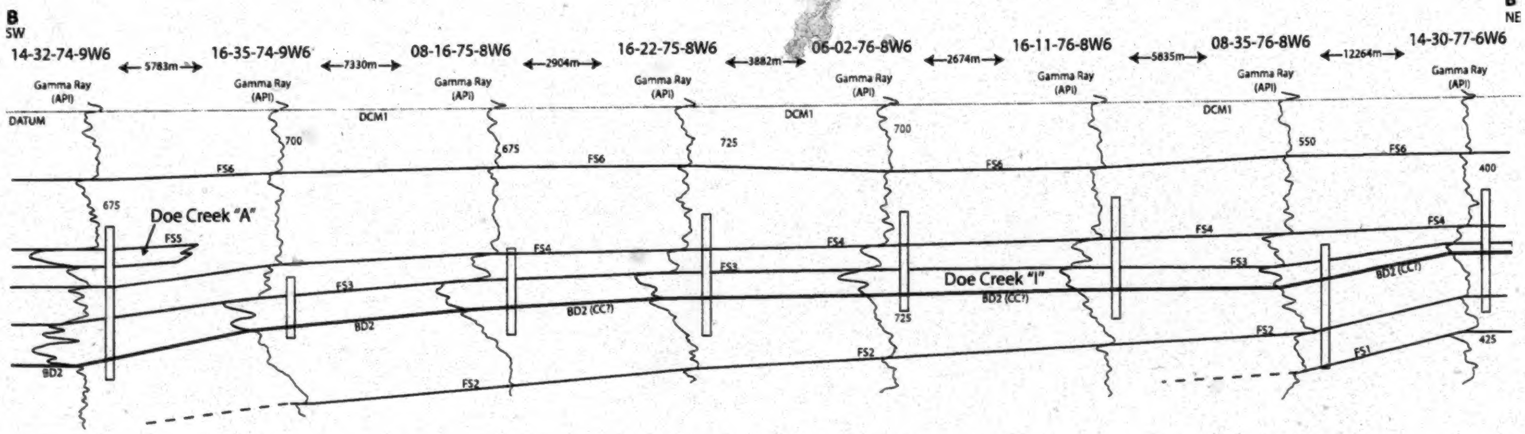

B
SW
B'
NE
14-32-74-9W6
16-35-74-9W6
08-16-75-8W6
16-22-75-8W6
06-02-76-8W6
16-11-76-8W6
08-35-76-8W6
14-30-77-6W6
5783m
7330m
2904m
3882m
2674m
5835m
12264m
Gamma Ray (API)
DATUM
DCM1
FS6
FS5
FS4
FS3
FS2
FS1
BD2
BD2 (CC?)
Doe Creek "A"
Doe Creek "I"
675
700
725
550
400
425

Figure 4.5. Well-log cross section B-B'. See Figure 1.1B for locations. Red line demarcates lowstand surface. Shaded boxes indicate cored intervals.

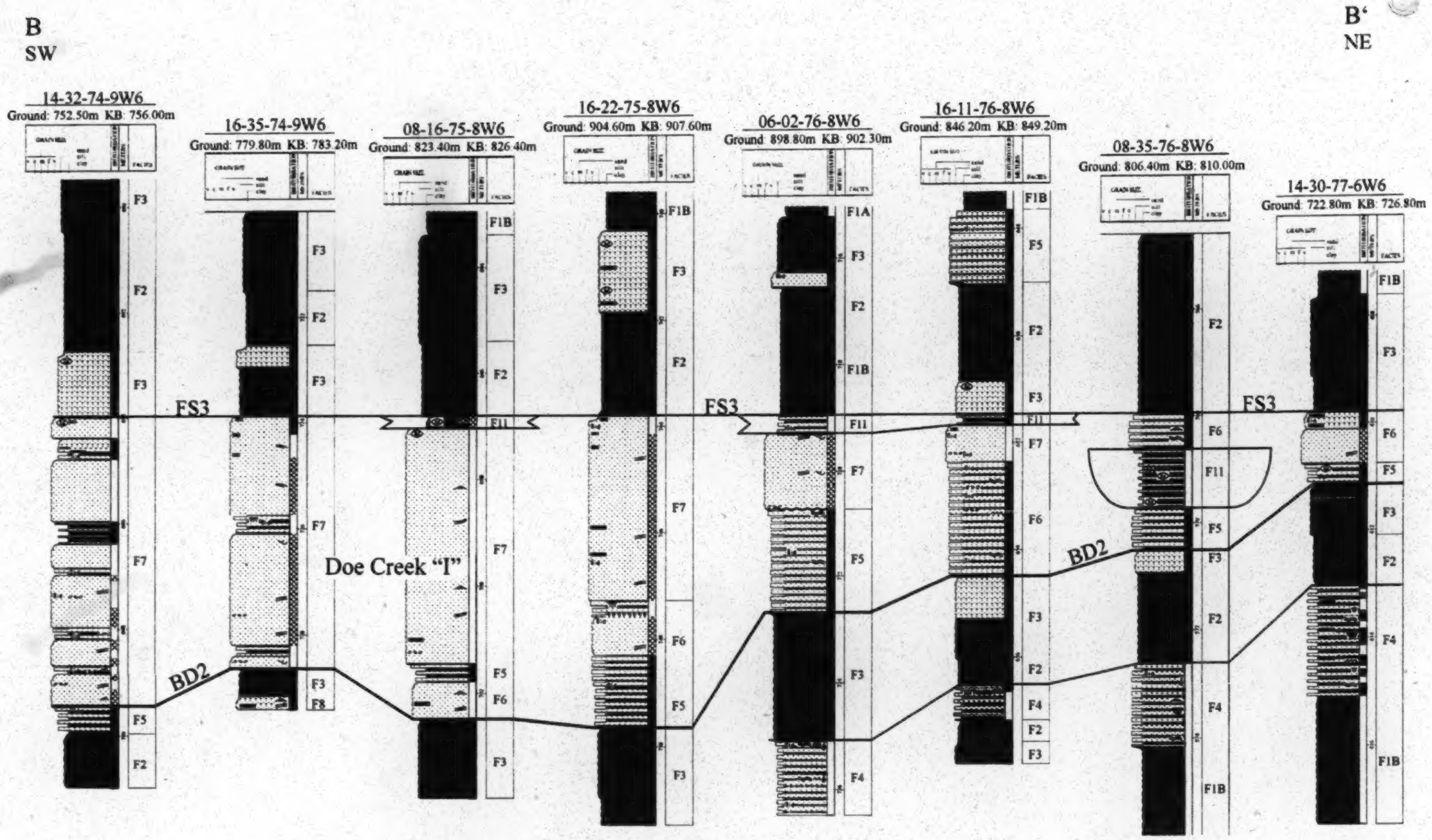

B
SW
B'
NE
14-32-74-9W6
Ground: 752.50m KB: 756.00m
16-35-74-9W6
Ground: 779.80m KB: 783.20m
08-16-75-8W6
Ground: 823.40m KB: 826.40m
16-22-75-8W6
Ground: 904.60m KB: 907.60m
06-02-76-8W6
Ground: 898.80m KB: 902.30m
16-11-76-8W6
Ground: 846.20m KB: 849.20m
08-35-76-8W6
Ground: 806.40m KB: 810.00m
14-30-77-6W6
Ground: 722.80m KB: 726.80m
FS3
FS3
FS3
BD2
BD2
Doe Creek "I"
F1A
F1B
F2
F3
F4
F5
F6
F7
F8
F11

Figure 4.6. Core cross section C-C'. See Figure 1.1B for locations.
Red line demarcates lowstand surface.

(approximately 430 m to the south) shows a possible channel form approximately 2 meters thick at the same stratigraphic interval. Therefore, the occurrence of Facies 11 in well 08-35 is interpreted to represent distributary abandonment or interdistributary bay deposits.

Cross section C-C' (Figure 4.7) is oriented parallel to depositional strike along the axis of the stratigraphically higher Doe Creek "A" sandstone. The datum used to hang the well log section is DCM1. There is at least one minor coarsening-upward cycle separating the Doe Creek "I" and Doe Creek "A" shoreline trends, visible on both the cross-sections B-B'. This thin package is highly variable across the study area and is absent in some wells. It typically manifests as a relatively thin shelf to offshore package with indications of deltaic influence. The discontinuity BD3 demarcates the "sharp-based" Doe Creek "A" sandstone but is actually only sharp based in association with the thickest deposits of delta front sandstone (F7A). BD3 is correlative with gradational contacts both to the northeast and southwest. Cross section C-C' shows lateral thinning of the sandstone body occuring to the southwest and northeast.

The core cross section C-C' (Figure 4.8) is hung on FS5 for ease of illustration. The distinctive lateral variation of Doe Creek shorelines is readily apparent in the transition from well 14-25-74-12W6 to 14-25-73-13W6. In well 14-25-74-12W6, BD3 is a sharp contact defining the base of a thick delta front sandstone body. In contrast BD3 becomes a correlative conformity (BD3/CC) in well 14-25-73-13W6, 13 km southwest along the shoreline. There, it defines the base of a gradational coarsening-upward cycle from distal lower offshore (F1A) to lower shoreface (F8), intercalated with thin prodeltaic deposits. This relationship clearly shows that the sharpness of "sharp-based" shorefaces can be predominantly facies controlled, which can be related the proximity of riverine point sources. The regressive package that can be seen in the upper portions of Figures 14 and 15, above FS5 and capped by FS5b, also displays remarkable lateral facies relationships. In the northeast, the regressive cycle is typified by a coarsening-upward shelf to shoreface cycle. In wells 14-25-74-12W6, 06-07-75-11W6, and 08-26-75-11W6 however, the shelf to shoreface succession is interrupted by delta deposits (F5 and F6). These prodelta and distal delta front deposits are encased in fully marine offshore and shoreface sediments. This indicates that a deltaic tongue of sediment must have prograded into the offshore, which may have significant exploration and exploitation implications. Within the Doe Creek Member, the delta front and associated distributary channels represent the reservoir facies with the best thickness development. If there are prodelta deposits intercalated with offshore and shoreface deposits, then there must have been contemporaneous delta front, and distributary deposits occurring up depositional dip. Therefore, these innocuous prodelta deposits, encased in fully marine offshore and shoreface deposits, can be a guide for future exploration targets.

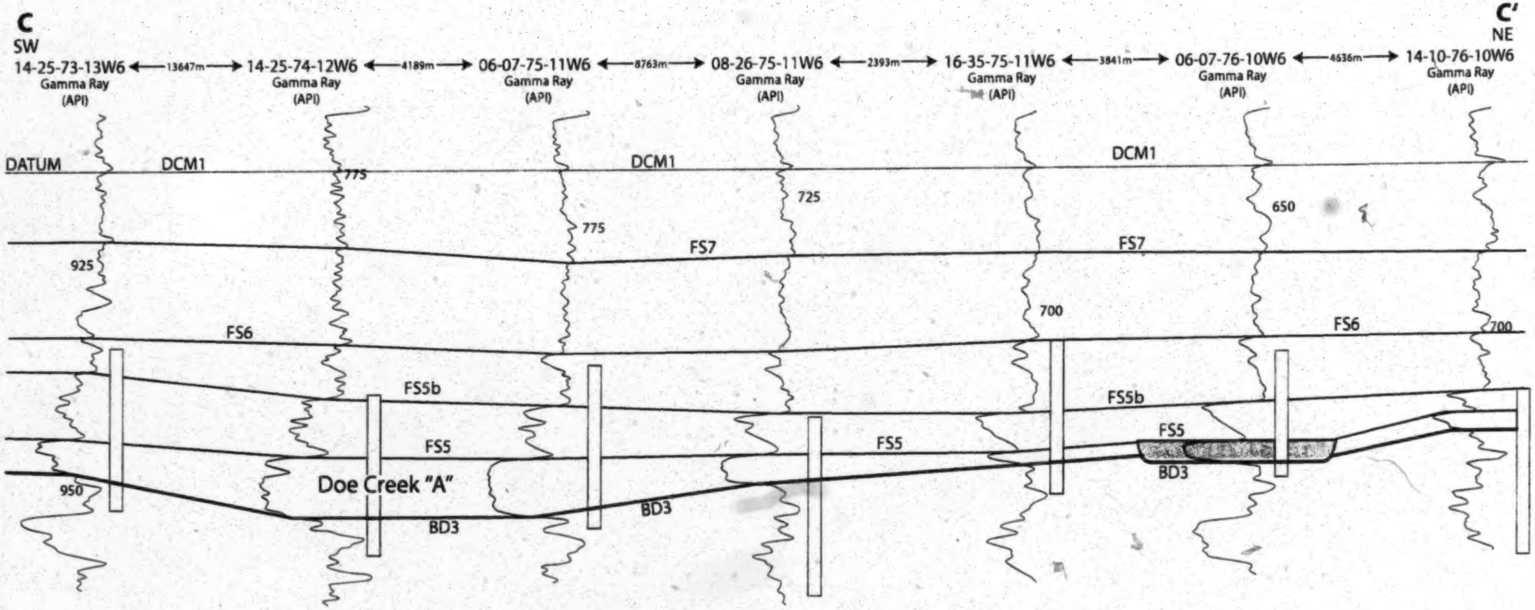

C
SW
C'
NE
14-25-73-13W6 Gamma Ray (API)
13647m
14-25-74-12W6 Gamma Ray (API)
4189m
06-07-75-11W6 Gamma Ray (API)
8763m
08-26-75-11W6 Gamma Ray (API)
2393m
16-35-75-11W6 Gamma Ray (API)
3841m
06-07-76-10W6 Gamma Ray (API)
4636m
14-10-76-10W6 Gamma Ray (API)
DATUM
DCM1
DCM1
DCM1
775
775
725
650
925
FS7
FS7
700
FS6
FS6
700
FS5b
FS5b
FS5
FS5
FS5
950
Doe Creek "A"
BD3
BD3
BD3

Figure 4.7. Well-log cross section C-C'. See Figure 1.1B for locations. Shaded boxes indicate cored intervals. Red line demarcates lowstand surface.

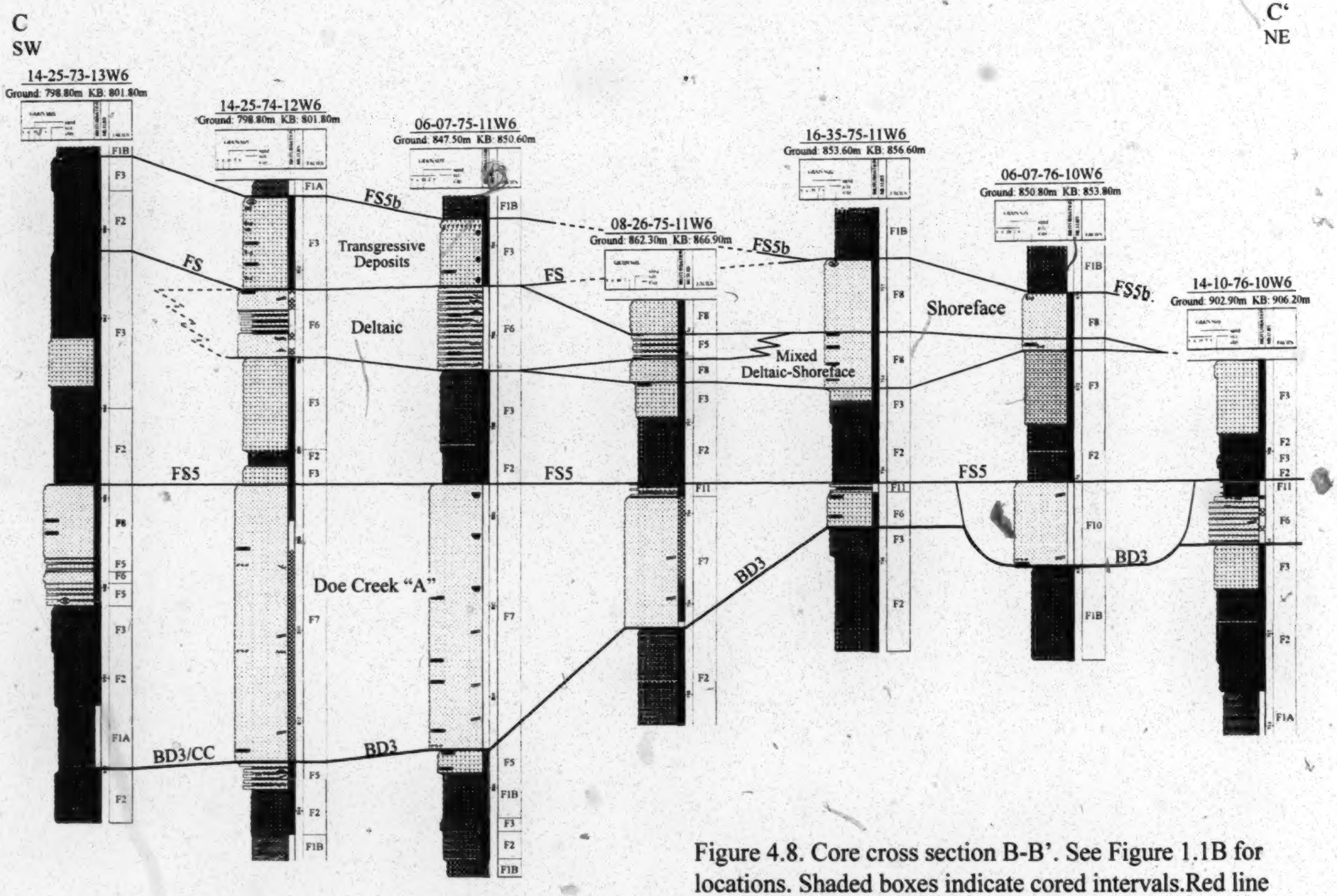
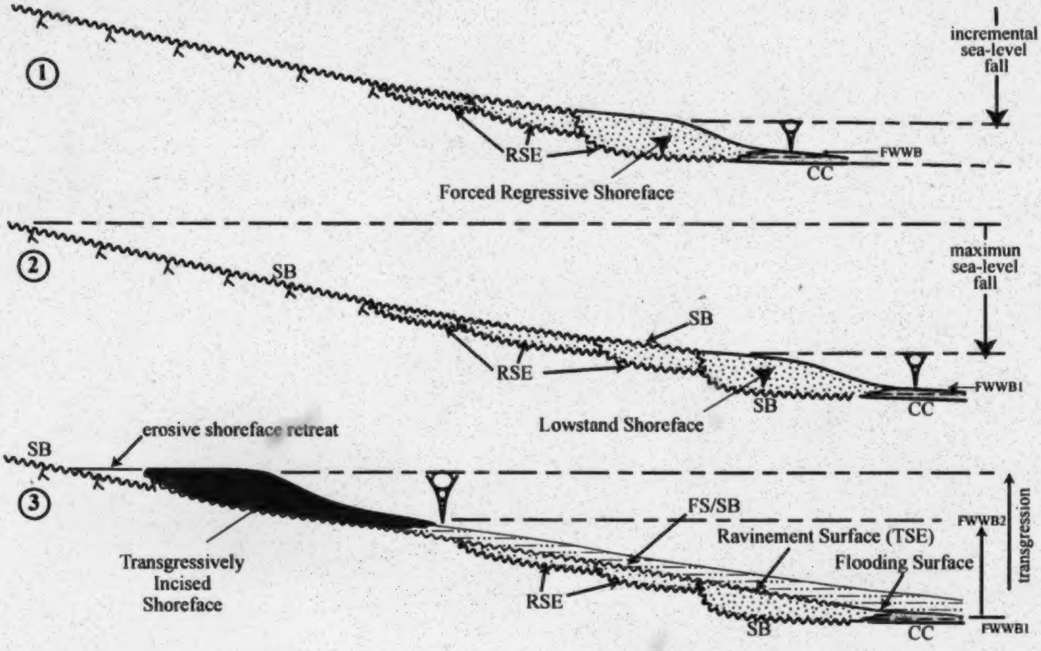

C
SW
C'
NE
14-25-73-13W6
Ground: 798.80m KB: 801.80m
14-25-74-12W6
Ground: 798.80m KB: 801.80m
06-07-75-11W6
Ground: 847.50m KB: 850.60m
08-26-75-11W6
Ground: 862.30m KB: 866.90m
16-35-75-11W6
Ground: 853.60m KB: 856.60m
06-07-76-10W6
Ground: 850.80m KB: 853.80m
14-10-76-10W6
Ground: 902.90m KB: 906.20m
FS5b
FS
FS5
BD3/CC
BD3
Transgressive Deposits
Deltaic
Doe Creek "A"
Mixed Deltaic-Shoreface
Shoreface
F1A
F1B
F2
F3
F5
F6
F7
F8
F10
F11

Figure 4.8. Core cross section B-B'. See Figure 1.1B for locations. Shaded boxes indicate cored intervals.Red line demarcates lowstand surface.

4.4 STRATIGRAPHIC EVOLUTION OF THE DOE CREEK MEMBER

The succession of Kaskapau Formation strata from the top of the Dunvegan Formation to the Second White Speckled Shale represents an overall transgressive package punctuated by smaller scale episodes of regression during stillstand or lowstand conditions. The sandstones of the Doe Creek Member are interpreted to have been deposited within lowstand shoreline systems as a result of these progradational events. The shallow-marine sandstones are isolated within marine shales and mudstones. The lower contact of the sandstone bodies within the Doe Creek Member are often sharp-based and are interpreted to reflect abrupt shallowing, rapid progradation and erosion. This character is consistent with that of a regressive surface of erosion (RSE) (cf. Hunt and Tucker, 1992; Hellend-Hansen and Gjeldberg, 1994; Mellere and Steel, 1995) and a sequence boundary at maximum lowstand (cf., Plint, 1988; Posamentier *et al.*, 1992; Van Wagoner, 1995). Sharp-based, or incised, shorefaces can correspond to forced regressive, lowstand, or transgressively incised systems (Figure 4.9). Highstand shorefaces also can generate a "sharp based" character caused by the erosive base of an individual storm bed, but typically lacks evidence of incision or truncation into regional markers in subjacent horizons (Pemberton *et al.*, 2004). The facies comprising the three types of incised shorefaces are essentially identical. The differentiation of incised shorefaces lies on the character of their basal contact and their relative emplacement within a single sequence. Forced regressive shoreface and/or delta deposits overlie regressive surfaces of erosion which cut in submarine conditions and pass seaward into conformable surfaces (MacEachern *et al.*, 1999b). The preservational potential of falling stage shoreface sandstones and the correlative conformities of regressive surfaces of erosion are low as they are exposed to further wave erosion during continued regression, the lowstand sequence boundary, and the subsequent transgressive surface of erosion. Lowstand shorefaces and/or deltas overlie the sequence boundary and its basinward correlative conformity (Posamentier *et al.*, 1992; MacEachern *et al.*, 1999b). Lowstand shorefaces occur at the most seaward extent of regression within a single sequence prior to subsequent sea-level rise leading to a much higher preservation potential, a key difference between lowstand and forced regressive and transgressively incised shorefaces. Transgressive shorefaces and/or deltas are underlain by a flooding surface sequence boundary cut by a transgressive surface of erosion. The erosive surface cut during transgression can ultimately lie seaward of fair-weather wave base during subsequent regression, leading to the potential of offshore deposits lying above the erosion surface (MacEachern *et al.*, 1999b). Due to the potential of a high degree of sediment winnowing via wave action during transgression, transgressive surfaces of erosion are commonly overlain by a lag deposits of coarse grained material, which is a variance from that of regressive surfaces of erosion and sequence boundaries cut during regression.



①
incremental sea-level fall
RSE
Forced Regressive Shoreface
FWWB
CC
②
SB
maximun sea-level fall
SB
RSE
SB
Lowstand Shoreface
FWWB1
CC
③
SB
erosive shoreface retreat
FS/SB
FWWB2
Ravinement Surface (TSE)
Flooding Surface
transgression
Transgressively Incised Shoreface
RSE
SB
CC
FWWB1

Figure 4.9. Differentiation of forced-regressive, lowstand, and transgressively incised shoreface complexes. (modified from MacEachern *et al.,* 1998).

The observations made in the stratigraphic analysis of the Doe Creek Member in the previous section are consistent with a lowstand shoreface and/or delta succession. Figure 4.10 illustrates the nature of the emplacement of the Doe Creek Sandstones in stratigraphic context as interpreted from the cross section analysis. The initial stage of Doe Creek Member deposition is dominated by marine shales deposited during transgression. Smaller order, relative sea-level oscillations cause the transgression to be punctuated by regressive events. During early highstand, the Doe Creek Shorelines undergo normal regression. During the falling stage (forced regressive stage), the Doe Creek Shorelines experience rapid progradation. This rapid progradation is caused in large part to the extremely low slope of the western margin of the foreland basin. This low-angle depositional profile is exaggerated by the thick deposits of the Dunvegan Formation underlying the Doe Creek Member, occupying most of the available accommodation space. Very little of the forced regressive deposits are recorded in the

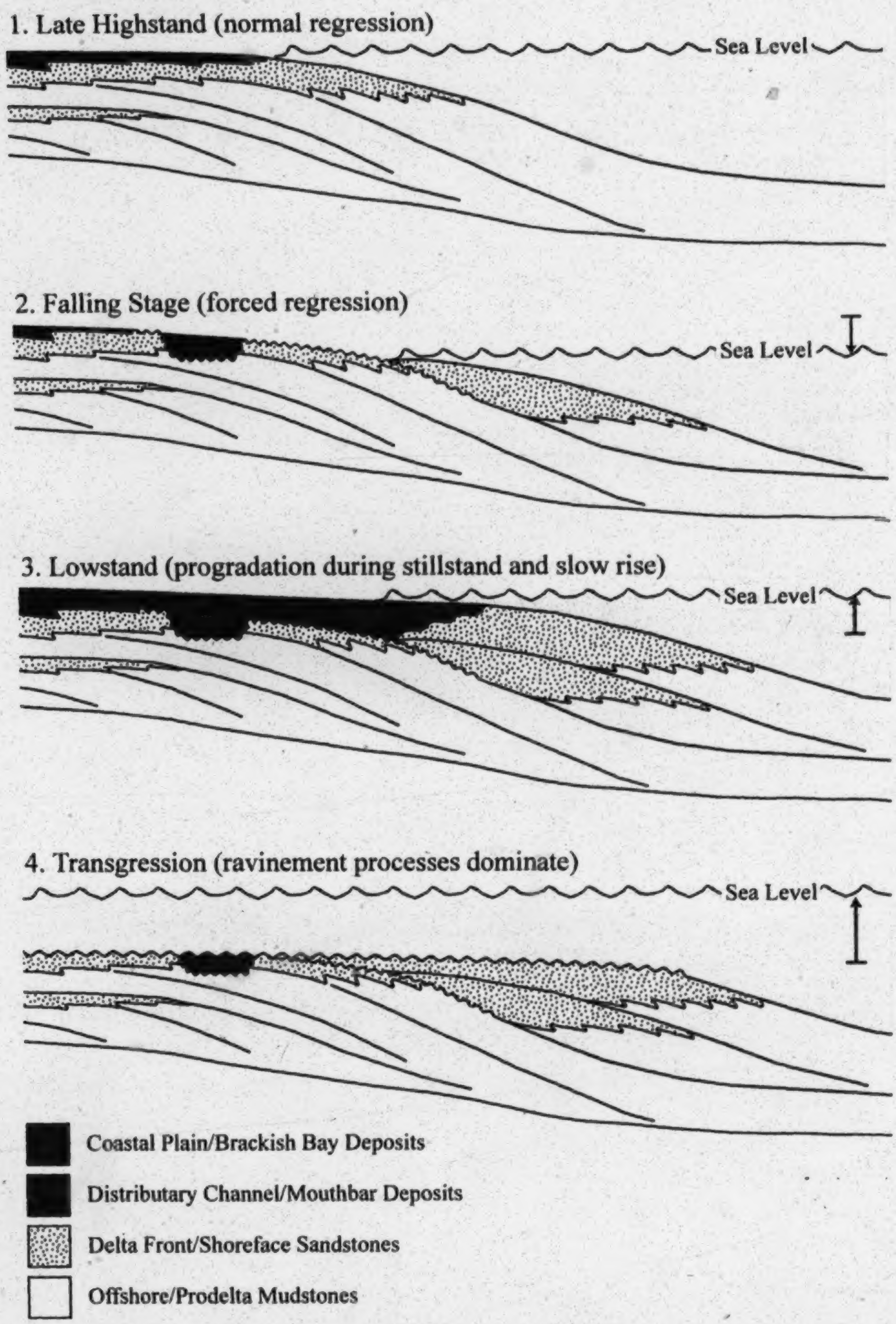

1. Late Highstand (normal regression)
Sea Level
2. Falling Stage (forced regression)
Sea Level
3. Lowstand (progradation during stillstand and slow rise)
Sea Level
4. Transgression (ravinement processes dominate)
Sea Level
Coastal Plain/Brackish Bay Deposits
Distributary Channel/Mouthbar Deposits
Delta Front/Shoreface Sandstones
Offshore/Prodelta Mudstones

Figure 4.10. Schematic diagram illustrating the emaplacement of the lowstand shorelines of the Doe Creek Member. (Modified from Bhattacharya, 1993).

Doe Creek Member. This is due in part to the nature of forced regressions whereby deposits are subaerially exposed during regression and further cannibalized by subsequent regressive surfaces and the sequence boundary, but also caused by the lack of accommodation space resulting in high probability of sediment bypass. The lowstand phase of the deposition is characterized by the incising of the sequence boundary into underlying strata resulting in the creation of accommodation. The Doe Creek shorelines filled this accommodation and prograded seaward into the basin as evidenced by the correlative conformity noted in this distal well of cross section A-A'. As transgression resumed, ravinement processes cannibalized and/or removed the majority of terrestrial deposits associated with the regressive phase of deposition. The only backshore deposits recorded are those of distributary channels and backshore bays.

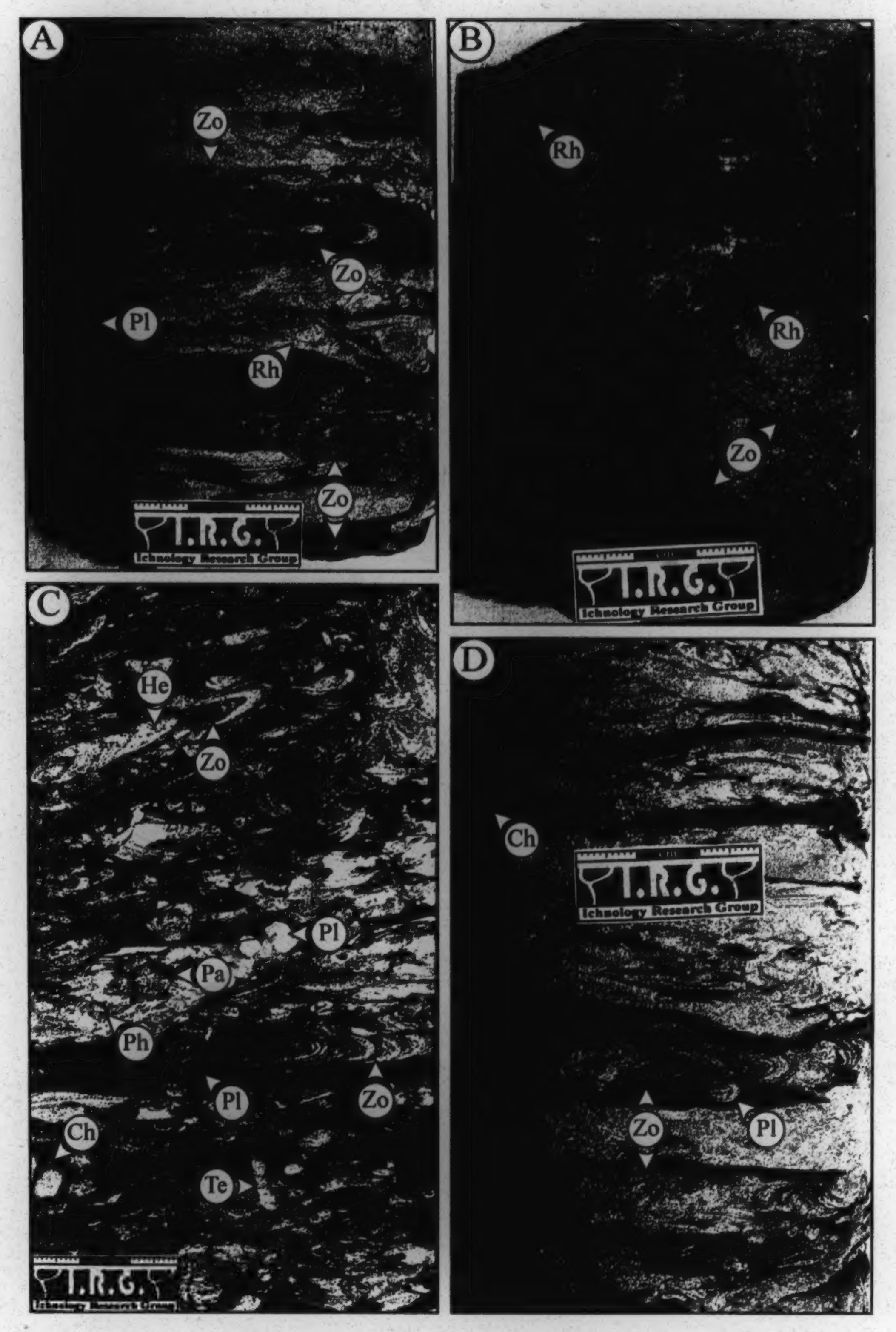
4.5 DEPOSITIONAL MODEL

The facies analysis of the Doe Creek Member elucidated a dichotomy in the origin of the coarsening-upward cycles in the Doe Creek. Based on the ichnological and sedimentological characteristics, the two facies associations were interpreted to reflect the deposits of a prograding delta and a prograding shoreface. The cross sections generated using core data and well logs allowed for an investigation of facies architecture. The strike oriented sections (Figures 4.5, 4.6, 4.7, and 4.8) illustrated the contemporaneity of the deposits of deltaic and open-marine shoreface origin. The two facies associations represent end members of a continuum of deposits which are controlled spatially. FA1 represents deposits of a prograding open-marine shoreface succession without a notable influence of riverine influx. Conversely, FA2 represents deposits of a prograding mixed river- and wave-dominated delta. The nature of the facies succession encountered in the Doe Creek Member is therefore dependant on proximity to the point source of riverine inflow into the basin.

Initial difficulty was encountered interpreting the atypical ichnology and sedimentology encountered in what was later deemed deltaic in origin. While the character of individual facies was consistent with those encountered in deltaic systems, the facies architecture and geometry were contrary to those predicted by facies models of deltas. However, most deltaic facies models have been generated based on study of delta systems such as the Mississippi, Niger, and Nile, which are some of the largest modern deltas, as well as ancient deltas which are equivalent in size to those found in the Dunvegan Formation and Ferron Sandstone. It is this author's opinion that the facies models of deltas have been biased to the large delta systems and are not readily applicable to small to moderate sized deltas such as those found in the Doe Creek Member. Deltas can occur as small lobate punctuations on an otherwise contiguous shoreline deposit. They may affect the shape of the resultant sandstone body due to differential progradation as well as potential thickness due to localized sedimentation as seen in the Doe Creek "I" net sand isopach (Figure 4.1). However, the deltaic influence may only serve to alter the ichnological and sedimentological character of the facies succession, and would require core data to recognize. As mentioned previously, the two facies associations are end members in a continuum of facies successions controlled by proximity to a deltaic point source. Encountered in the Doe Creek are several units which are difficult to attribute to either the fully marine offshore facies or the prodeltaic facies. Figure 4.11 contains examples of units which can be attributed to a mixed origin, or that of moderate delta influence. This type of facies could easily be overlooked as an

Figure 4.11. Offshore deposits displaying a moderate deltaic influence (Mixed deltaic and open-marine signature.

A-D). The examples shown here are not readily classifiable as Facies 2/Facies 3 (open marine offshore) or Facies 4/Facies 5 (prodelta). These rocks are best described as offshore deposits with moderate deltaic influence. The deltaic influence is evident by the anomalous organic-rich mud beds. These mud beds are typical of the prodelta deposits seen in the Doe Creek Member, originating as storm-related deposits or as fluid mud. However the high bioturbation intensities and diversity of ichnogenera indicate a low-stress environment. Ichnogenera present include *Zoophycos* (Zo), *Rhizocorallium* (Rh), *Planolites* (Pl), *Phycosiphon* (Ph), *Chondrites* (Ch), *Teichichnus* (Te) and *Palaeophycus* (Pa). A) Well 14-32-74-9W6, depth 685.8m. B) Well 16-34-76-9W6, depth 662.36m. C) Well 10-23-72-11W6, depth 1078.8m. D) 06-02-76-8W6, depth 722.9m.


A
Zo
Zo
Pl
Rh
Zo
I.R.G.
Ichnology Research Group
B
Rh
Rh
Zo
I.R.G.
Ichnology Research Group
C
He
Zo
Pl
Pa
Ph
Pl
Zo
Ch
Te
I.R.G.
Ichnology Research Group
D
Ch
I.R.G.
Ichnology Research Group
Zo
Pl

anomaly of an open-marine facies. However, careful examination of feature such as fluid mud deposits, hyperpycnal flow deposits, and a subtly modified ichnologic assemblage, reveals the complex nature of the unit. Figure 4.12 presents a depositional model illustrating the realtionship of facies in the Doe Creek Member.

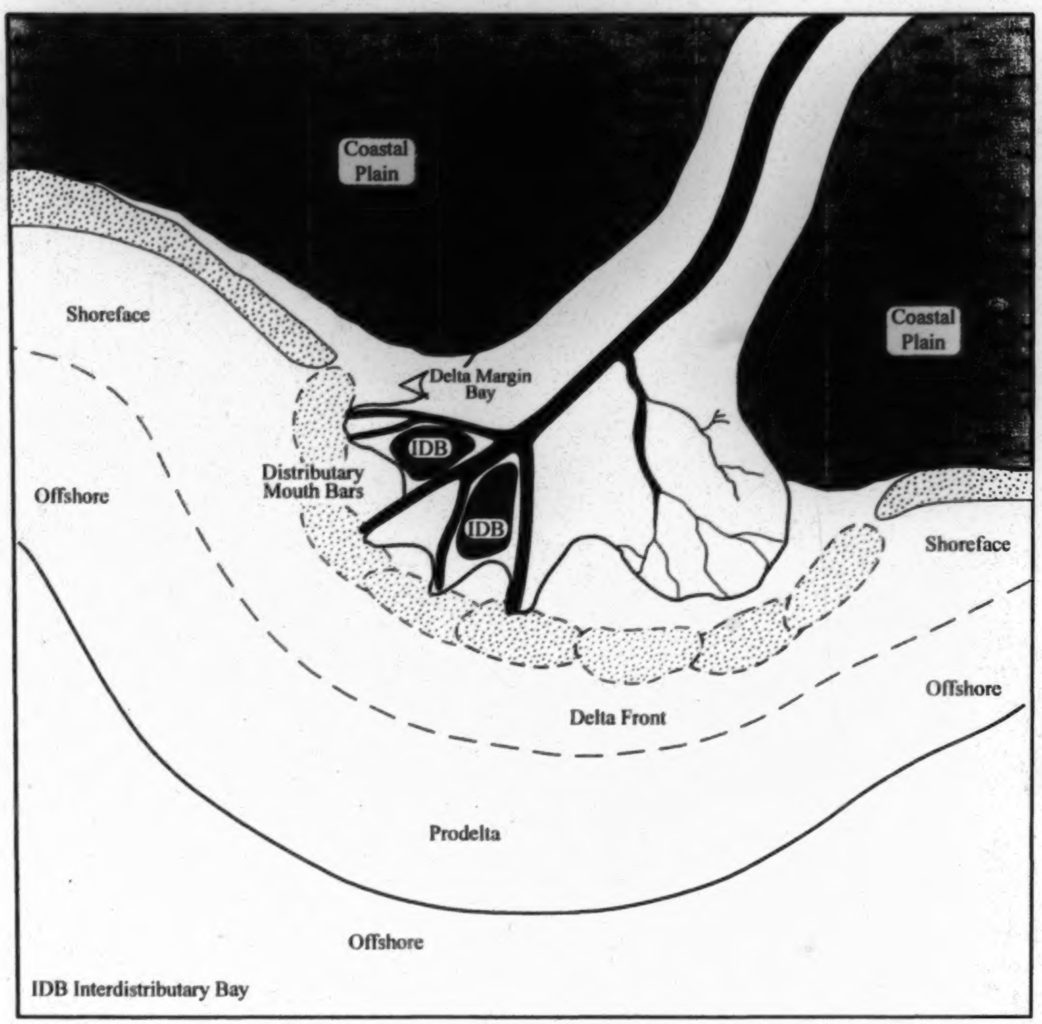

Coastal Plain
Coastal Plain
Shoreface
Delta Margin Bay
IDB
IDB
Distributary Mouth Bars
Offshore
Shoreface
Offshore
Delta Front
Prodelta
Offshore
IDB Interdistributary Bay

Figure 4.12. Schematic depositional model illustrating a hypothetical scenario of the Doe Creek Shoreline systems.

CHAPTER 5

RECOGNIZING SUBAQEOUS DELTA SUCCESSIONS

5.1 INTRODUCTION AND BACKGROUND

Historically, the delineation of deltaic deposits in the ancient record has relied heavily on physical sedimentary structures and the large scale, three-dimensional geometry. Thorough depositional models for deltas have been well documented and are generally well understood in both the modern and ancient record (e.g. Scruton, 1960; Coleman et. al., 1964; Coleman and Gagliano, 1965; Wright and Coleman, 1973; Coleman and Wright, 1975; Coleman, 1981; Weise, 1980; Howard and Nelson, 1982; Bhattacharya and Walker, 1991a, 1991b; Bhattacharya, 1993). Deltas are classically defined as "discrete shoreline protuberances formed where a river enters a standing body of water (i.e. ocean, sea, lake, estuary) and supplies sediment more rapidly than can be redistributed by basinal processes" (Elliot, 1986). This broad categorization can be divided into two main types; 1) shelf deltas, which are defined as deltas prograding across a shallow water shelf or epeiric sea; and 2) shelf-margin deltas, which occur in proximity to the shelf-slope break (Elliot, 1989). This is an important distinction to consider when creating and applying deltaic depositional models, as shelf deltas and shelf-margin deltas display markedly dissimilar macro-scale features and geometry. The key differences are that shelf and epeiric sea deltas are characterized by extensive delta front sands, significant progradation distances, and lack of large-scale growth faulting (Elliot, 1989). Deltaic depositional systems are generally broken down further into the wave-, tide- and river- dominated end-members (Galloway, 1975) based on the relative magnitude of riverine sediment influx, basinal wave energy, and tidal regime (Figure 5.1). These parameters govern the external morphology, internal stratigraphy, and facies architecture of the delta.

Difficulty in recognizing ancient deltas arises because their deposits cannot be summarized in terms of a single facies model (Elliot, 1989). Coastal shoreface and deltaic environments occur laterally adjacent and transitional with one another on clastic shorelines making their distinction problematic (Moslow and Pemberton, 1988). Deltaic and shoreface systems also display broad similarity in coarsening-upward cycles successions related to progradation.

It is only recently that ichnological analysis has been applied to the recognition of deltaic facies. The application of ichnological analysis and the ichnofacies concept

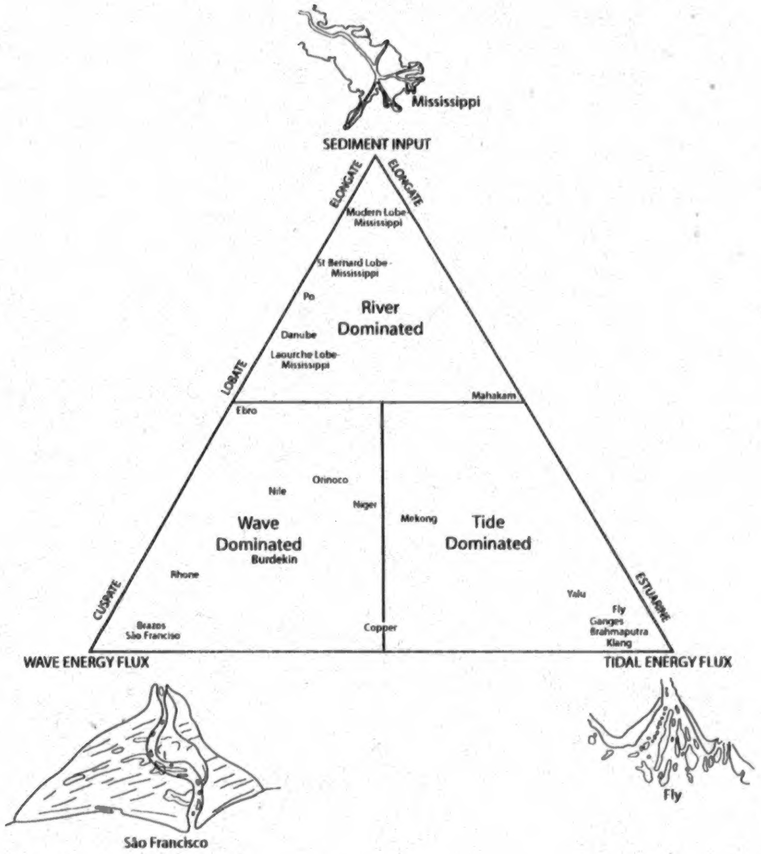

Mississippi
SEDIMENT INPUT
ELONGATE
ELONGATE
Modern Lobe-Mississippi
St Bernard Lobe-Mississippi
Po
River Dominated
Danube
Laourche Lobe-Mississippi
LOBATE
Mahakam
Ebro
Orinoco
Nile
Niger
Mekong
Wave Dominated
Burdekin
Tide Dominated
Rhone
CUSPATE
ESTUARINE
Yalu
Fly
Ganges
Brahmaputra
Klang
Brazos
São Franciso
Copper
WAVE ENERGY FLUX
TIDAL ENERGY FLUX
Fly
São Francisco

Figure 5.1. The tripartite classification of deltas based on the predominance of river, wave, or tidal forces. (after Galloway, 1975).

has proven to be an invaluable tool in the field of paleoenvironmental analysis. Research has shown that trace fossils record the behavioral response of an organism to specific parameters in the immediate environment such as sedimentology, chemistry, and bathymetry (Seilacher, 1955, 1967; Howard and Frey, 1984; Frey and Pemberton, 1985; Frey *et al.,* 1990; Pemberton *et al.,* 1992a, Pemberton *et al.,* 2001). Numerous integrated ichnologic and sedimentologic studies of Cretaceous "offshore to beach" successions in the western interior seaway of North America have demonstrated the significant improvements ichnologic analysis made to the interpretation of shallow marine and marginal marine deposits (e.g. Howard and Frey, 1984; Frey and Howard, 1985, 1990; Howard and Reineck, 1981; MacEachern and Pemberton, 1992, 1994; MacEachern *et al.,* 1992, 1999a; Pemberton and Wightman, 1992; Pemberton *et al.,* 1992a, 2001).

Moslow and Pemberton (1988) presented a study of the ichnological signature of delta deposits as compared to those of open-marine shoreface succession utilizing core from the Cadotte Member of the Peace River Formation and Bluesky Formation. The ichnological signature of the Bow Island Formation was studied by Raychaudhuri and Pemberton (1992) and Raychaudhuri (1994). Gingras *et al.* (1998) performed an analysis of the ichnological signature of wave- and river-dominated delta systems in the Dunvegan Formation. This preliminary work on the Dunvegan Formation was followed up by Coates and MacEachern (1999, 2000), Coates (2001), and MacEachern and Coates (2002) which included evaluation of delta systems in the Belly River Formation. Bann and Fielding (2004) evaluated and compared deltaic and open-marine shoreface deposits in Permian units in the Sydney-Bowen basin in Australia. More recently MacEachern *et al.* (2005) presented a synthesis of deltaic influences on infaunal communities and the resulting ichnological assemblages.

The Doe Creek Member presents a unique opportunity to evaluate and compare deltaic and open-marine shoreface systems, contributing to the presently sparse data set of ancient examples. The facies analysis conducted for this study revealed deltaic and non-deltaic facies succession exist in close proximity laterally along individual shorelines. This juxtaposition allows for comparison of coeval deposits mitigating the possibility of changes in climate, basin configuration, drainage patterns etc. to bias the data. The comparison of Doe Creek deltaic and non-deltaic shoreline deposits will focus on the offshore deposits, which are sediments deposited below fair-weather wave base and above storm (maximum) wave base. The delta front and shoreface facies occurring in the Doe Creek Member are quite similar in most regards. This is a common occurrence in wave-influenced delta systems as fair-weather and storm-weather wave processes are more prevalent than those of the tidal system and riverine outflows (Gingras *et al.*, 1998; Coates and MacEachern, 1999; Coates, 2001; MacEachern and Coates, 2002). The offshore deposits of the Doe Creek Member comprise a well developed, unstressed *Cruziana* ichnofacies. The presence of an unstressed ichnological assemblage provides a baseline for comparison with the deltaic successions. River derived stresses can have a profound impact on infaunal colonization and include salinity changes, heightened and/or variable sedimentation rate, hypopycnal flow induced water turbidity, distributary flood disharges with associated phytodetrital pulses, hyperpycnal flow induced sediment gravity flows, and fluid-mud deposition (MacEachern *et al.*, 2005). These stresses limit the diversity of biota present and can cause marked behavioral changes in the remaining organisms.

5.2 THE OFFSHORE

The marine offshore is generally placed below minimum (fair-weather) wave base and above maximum (storm) wave base (Pemberton *et al*., 2001), and is characterized ichnologically by the *Cruziana* ichnofacies. The benthic environment associated with the *Cruziana* ichnofacies is typified by moderate to relatively low energy, well-sorted silts and sands to interbedded muddy and clean sands, with minimal to appreciable sedimentation rates (Pemberton *et al*., 2001). Ichnologically, the *Cruziana* ichnofacies is dominated by feeding and grazing structures constructed by deposit feeders and displays both high diversity of ichnogenera and abundance of bioturbation (Figure 5.2). Typical trace fossil forms include abundant epistratal and intrastratal crawling traces, inclined U-shaped burrows displaying predominantly protrusive spreiten indicative of feeding swaths, *Ophiomorpha* and *Thalassinoides* composed of irregularly inclined to horizontal components, less common vertical cylindrical burrows of suspension feeders and passive

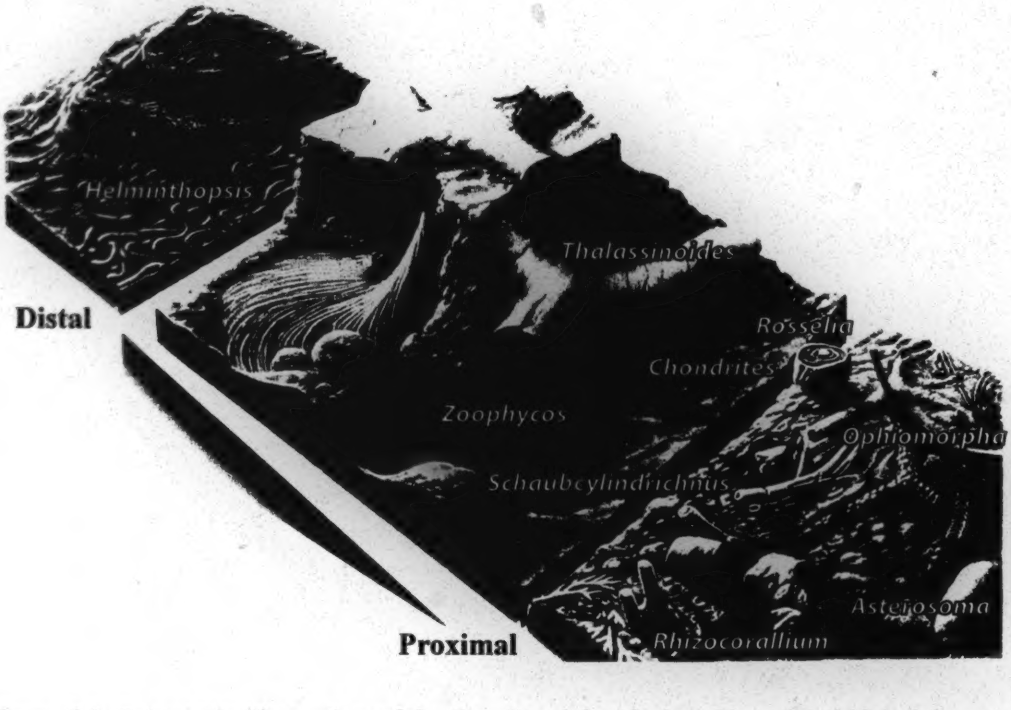

Helminthopsis
Thalassinoides
Distal
Rosselia
Chondrites
Zoophycos
Ophiomorpha
Schaubcylindrichnus
Asterosoma
Proximal
Rhizocorallium

Figure 5.2. Schematic illustration of the Cruziana ichnofacies . Note the shift in ichnological assemblages from distal to proximal settings. (Artistic representation produced by Tom Saunders).

carnivores. Food materials can be found both in suspension and deposited as detritus due to a high degree of variability inherent in environmental parameters affecting the water column and the sea floor. The ichnological community therefore represents a combination of suspension and deposit feeders.

The sedimentology and sedimentary textures encountered in the bathymetric zone of the *Cruziana* ichnofacies can display substantial variability. Physical sedimentary structures are often completely destroyed due to substrate homogenization via biogenic reworking. However, where preserved, structures include parallel to sub-parallel low angle cross laminations (most likely related to storm induced hummocky and/or swaley cross-stratification), wavy parallel to wave-ripple cross-lamination, and trough cross-bedded or megarippled sand in the proximal setting (Pemberton *et al.*, 2001).

The fully marine trace fossil assemblage of the Doe Creek Member is best expressed in the *Cruziana* ichnofacies. The aforementioned variability in environmental parameters associated with the *Cruziana* ichnofacies typically yields the most diverse suites of trace fossils. The offshore may be subdivided into the lower and upper offshore, differentiated based on the degree of storm and fair-weather wave interaction with the substrate of the sea floor (e.g. Pemberton *et al.,* 1992a).

The lower offshore facies of the Doe Creek Member is generally comprised of silty shales that are commonly homogenized by bioturbation. These silty shales are rarely interrupted by thin (cm-scale), normally graded silty sands resulting from distal tempestite deposition. Typical ichnogenera include *Phycosiphon, Helminthopsis, Schaubcylindrichnus, Planolites, Zoophycos, Chondrites, Thalassinoides,* and *Palaeophycus* representing the distal expression of the *Cruziana* ichnofacies. Rare, yet important, elements of the distal *Cruziana* ichnofacies are the opportunistic colonizers brought to the lower offshore either as larvae or adults during storm events (see discussion by Pemberton and MacEachern, 1997). These transported individuals, if they survive, may colonize the substrate of the lower offshore and produce a juxtaposition of the distal *Cruziana* assemblage with ichnogenera typically associated with higher energy ichnofacies such as the *Skolithos* ichnofacies. The most common examples of these ichnogenera are *Skolithos, Diplocraterion,* and *Ophiomorpha*.

The upper offshore facies of the Doe Creek Member are generally more variable in terms of sedimentological characteristics and contain a more diverse ichnological signature due to the increase in storm and wave influence in the water column and on the substrate. The upper offshore can be subdivided into "proximal" and "distal" settings based on the nature and/or presence of suspension feeding structures such as *Skolithos,* *Arenicolites,* and *Diplocraterion.* Sedimentologically the "distal" upper offshore generally displays intensely bioturbated silty and sandy shales. These silty and sandy shales are typically bioturbated to such a degree that primary sedimentary structures are completely destroyed making recognition of the nature of the bioturbated texture vital. Sandstone beds exhibiting an upwards increase in bioturbation intensity occur, representing large storm beds subsequently recolonized or amalgamated storm events in which fair weather bioturbation patterns were not preserved. Burrowing in the "distal" upper offshore is typically intense, very diverse, and displays an even distribution of ichnogenera. The upper offshore is ichnologically more diverse than the lower offshore with ichnogenera including *Planolites, Teichichnus, Palaeophycus, Thalassinoides, Helminthopsis, Zoophycos, Phycosiphon, Chondrites, Ophiomorpha, Rhizocorallium, Siphonichnus, Asterosoma, Scolicia,* rare *Rosselia*, as well as *Diplocraterion* and *Skolithos* associated with tempestite deposition.

The "proximal" upper offshore, while still dominated by grazing and foraging structures, does display limited suspension feeding structures such as *Diplocraterion* and *Skolithos* in the fair-weather suite as compared to the storm-dominated suite in the "distal" offshore. These suspension feeding structures along with other ichnogenera typically associated with the higher energy *Skolithos* ichnofacies such as *Teichichnus, Rosselia, Arenicolites,* and vertical *Ophiomorpha* typically cross-cut the archetypal *Cruziana* ichnogenera except where deep tier structures such as *Zoophycos* are still prevalent.

5.3 THE PRODELTA

The bathymetric range of prodeltaic deposits is equivalent to that of the offshore resulting in a *shoreline parallel* relationship (Figure 5.3). The prodelta facies in the Doe Creek Member is characterized sedimentologically by distinctly interbedded dark silty mudstones with fine- to very fine- grained sandstone beds of varying thicknesses. Common in the prodelta are sharp-based mudstones and shales that are abnormally high in total organic content interpreted to be the distal expression of hyperpycnal density currents discharged from a fluvial source or from suspension from rapid flocculation of hypopycnal plumes. Primary sedimentary structures include small and large-scale hummocky cross-stratification, wave- and combined flow cross lamination, and massive bedding. Soft sediment deformation is common in the prodelta and includes contorted bedding and synsedimentary faulting. Synaeresis cracks are also common. Primary sedimentary structures are more commonly preserved in the prodelta than in open-marine

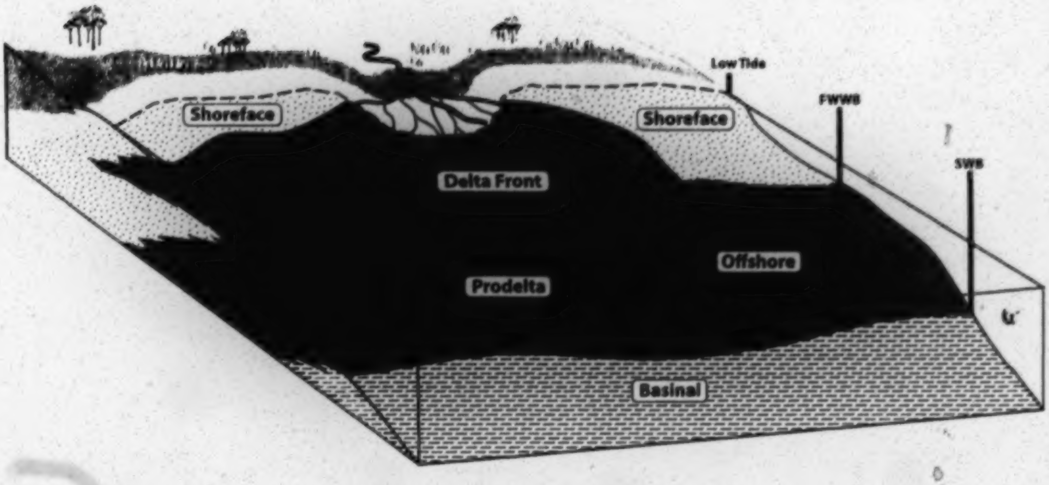


Figure 5.3. Schematic illustration demonstrating the depositional relationships between the deltaic and open-marine shoreface terminology used in this study.

offshore settings to the decrease in bioturbation intensity.

The behavior of the *Zoophycos* trace makers in the prodelta facies of the Doe Creek appears to differ from that of the fully marine offshore. The ethologic interpretation of *Zoophycos* remains a contentious issue (see Simpson, 1970; Ekdale and Lewis, 1991; Kotake, 1989,1991; Bromley, 1991; Bromley and Hanken, 2003; Löwemark and Schäfer, 2003). There are at least five competing models for the ethological interpretation of *Zoophycos* (Bromley and Hanken, 2003; Löwemark and Schäfer, 2003). Several deposit feeding models have been proposed to explain the behavior resulting in the *Zoophycos* morphology, (Seilacher, 1967; Simpson, 1970; Ekdale and Lewis, 1991). Kotake (1989, 1991) proposed a "waste stowage" model whereby the animal feeds at the sea floor from a stationary shaft and excretes waste at depth (Figure 5.4) which is consistent with some examples of *Zoophycos* in the Doe Creek (Figure 5.5). The ballast model (Bromley 1991) postulated that the animal feeds at depth, excretes waste at the surface and backfills the feeding structure cavity with sediment from the surface. Jumars et. al (1990) proposed the Cache model in which the *Zoophycos* animal stores food materials at depth in case of a temporary disruption of food supply occurs. The act of gardening was put forward by Bromley (1991) where the organism cultures micro-organisms at depth on a biogenically deposited organic rich substrate. The *Zoophycos* trace-makers have occured from water depths of greater than 1000 meters in the modern (Löwemark and Schäfer, 2003) to estimated water depths of 10's of meters in portions of the Doe Creek member.

It is possible that all five interpretations may be correct and that there are differing

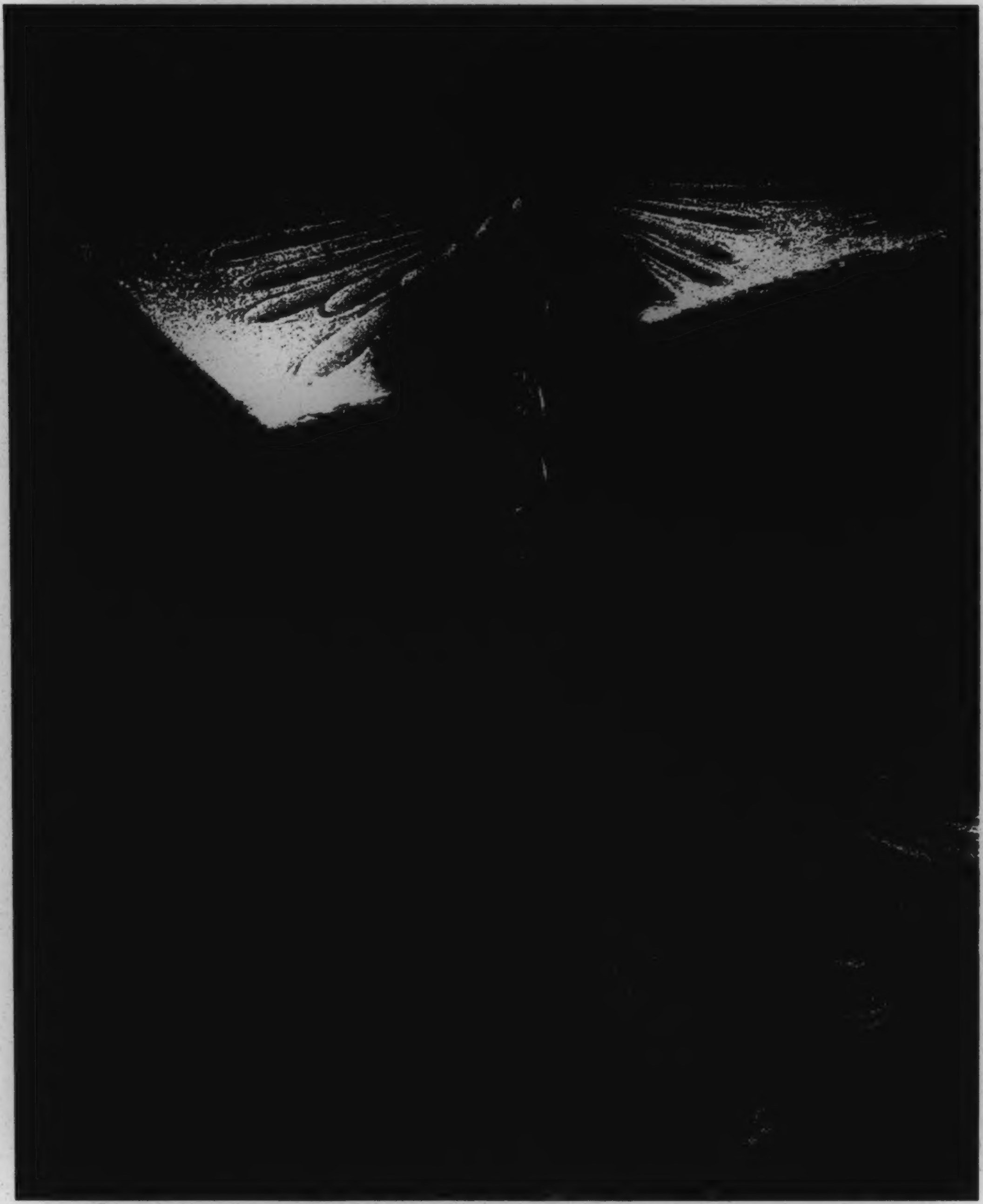


Figure 5.4. Schematic illustration of the "Kotake" model of *Zoophycos* ethology. Artistic representation created by Tom Saunders.

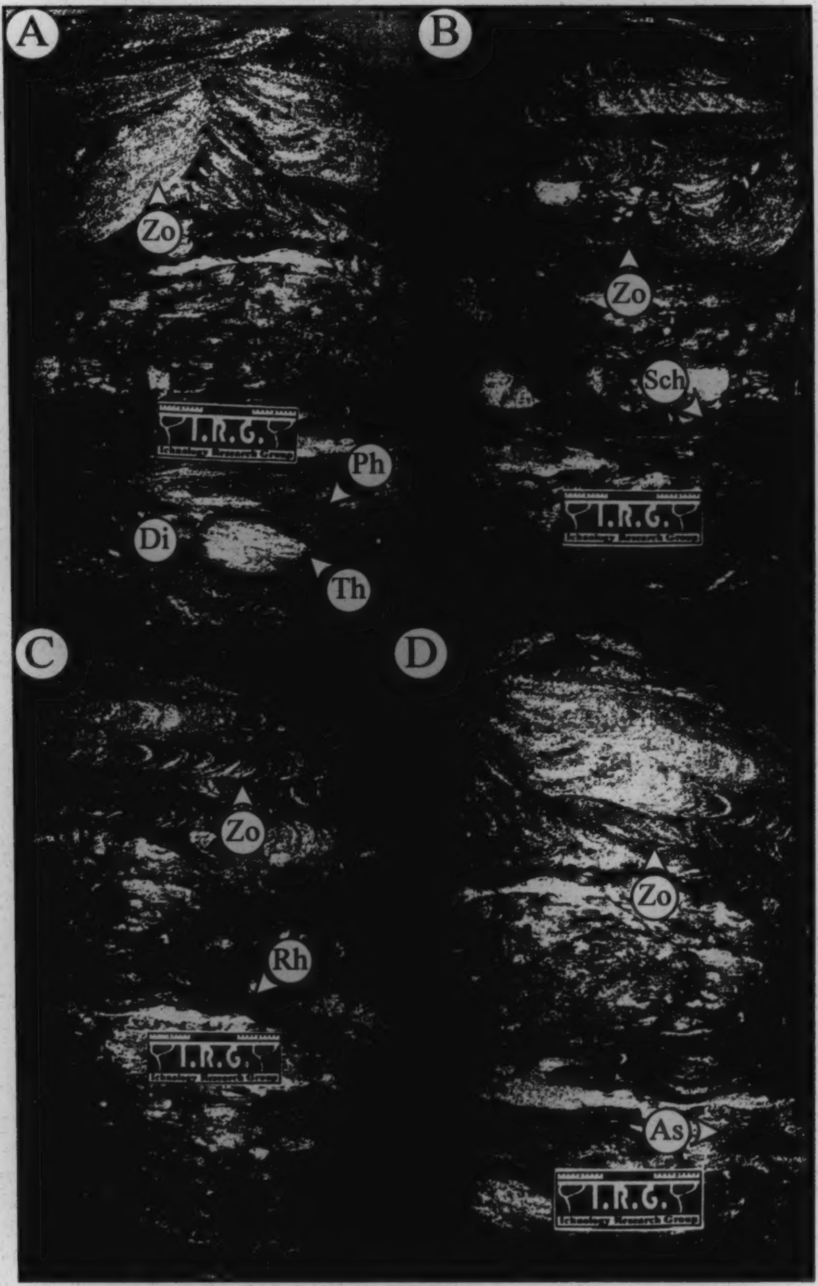

A
B
C
D
Zo
Zo
Sch
Ph
Di
Th
Zo
Rh
Zo
As
I.R.G.
Ichnology Research Group

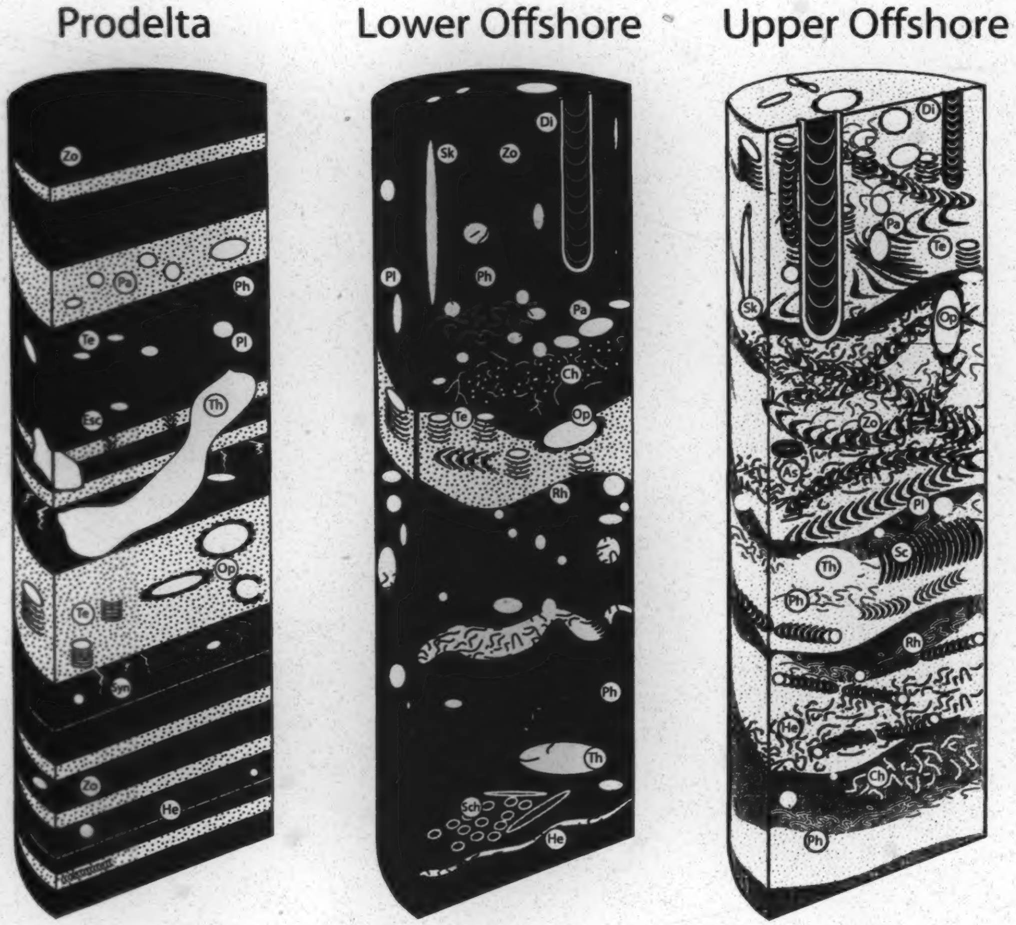
Figure 5.5. A)-D) These four pictures are successive, clockwise rotations about the axis of the core. The upper portion of the core displays a well developed, strictly patterned example of *Zoophycos* (Zo). This particular specimen is significant as it clearly shows a marked resemblance to deep-sea, waste stowage type *Zoophycos* (see text for discussion) (cf. Kotake 1989, 1991). *Zoophycos* (Zo), *Rhizocorallium* (Rh), *Phycosiphon* (Ph), *Diplocraterion* (Di), *Schaubcylindrichnus freyi* (Sch), *Asterosoma* (as). Well 14-25-73-13W6, depth 943.3m.

ethological behaviors that can result in very similar structures. However one can separate the behavior of *Zoophycos* into two broad categories; 1) behaviors responding to "steady-state" conditions at the sediment-water interface; and 2) behaviors responding to variable conditions at the sediment-water interface. In steady-state conditions *Zoophycos* will behave in a predictable stable manner as in Kotake's waste-stowage model creating well defined sub-parallel, sub-horizontal, uniform lobes. When conditions at the sea floor are unpredictable, the *Zoophycos* trace maker may alter its behavior accordingly, the most common effect being a shift from grazing at the sea-floor to grazing at depth. For instance *Zoophycos* may reflect behavior whereby it preferentially burrows in the muddy beds and may even rework a previous lobe structure. This pattern may point to the fact that conditions at the surface may not be suitable for sea floor feeding possibly due to sedimentation rate, turbidity, or hydraulic energy. This modified behavior is common in the "proximal" upper offshore and is especially distinctive in prodeltaic successions.

The prodelta facies of the Doe Creek Member exhibit a "stressed" *Cruziana* assemblage characterized by 1) sporadic distribution of bioturbation; 2) a reduction in the diversity of ichnogenera, abundance of individual ichnogenera, and intensity of burrowing; 3) an increase in the amount of deposit feeding traces; 4) reduction in size of ichnogenera; and 4) a modification of behavior of certain organisms. Because the stresses of the prodelta have a temporal nature and only affect the substrate periodically, fully marine ichnogenera such as *Zoophycos* and *Helminthopsis* are present, but in limited abundance and occurrence. The presence of such fully marine forms is fundamental to differentiating prodelta deposits from other stressed, brackish- water environments. The stresses of the prodelta are most prevalent in the water column and near the sediment water interface; therefore the *Zoophycos* trace maker may alter its feeding strategy from that of a sea-floor grazer to a substrate miner in an attempt to minimize exposure (Figure 3.9C).

5.4 ICHNOLOGICAL MODEL OF THE OFFSHORE AND PRODELTA

The open-marine deposits of the Doe Creek Member display a well developed, unstressed offshore ichnological assemblage which contrasts appreciably with the ichnological character of the stressed prodeltaic successions. The offshore deposits of the Doe Creek Member are characterized by poorly sorted mudstones and muddy sandstones displaying moderate to pervasive bioturbation, a diverse ichnological assemblage, and uniform distribution of ichnogenera. The prodelta facies while deposited in a similar bathymetric regime as the open-marine offshore deposits are


Prodelta

Lower Offshore

Upper Offshore

Zo
Pa
Ph
Te
Pl
Th
Esc
Op
Te
Syn
Zo
He
Di
Sk
Zo
Pl
Ph
Pa
Ch
Te
Op
Rh
Ph
Th
Sch
He
Di
Pa
Te
Sk
Op
Zo
As
Pl
Sc
Th
Ph
Rh
He
Ch
Ph

Figure 5.6. Schematic representation of the sedimentological and ichnological differences between prodelta and offshore deposits, based on observations in the Doe Creek Member of Kaskapau Formation. *Zoophycos* (Zo), *Phycosiphon* (Ph), *Planolites* (Pl), *Scolicia* (Sc), *Palaeophycus* (Pa), *Thalassinoides* (Th), *Ophiomorpha* (Op), *Skolithos* (Sk), *Chondrites* (Ch), *Teichichnus* (Te), *Helminthopsis* (He), *Rhizocorallium* (Rh), fugichnia (esc), *Diplocraterion* (Di), *Schaubcylindrichnus freyi* (Sch), and *Asterosoma* (As).

characterized by interbedded claystones, siltstones, and sandstones displaying low to moderate bioturbation, a somewhat impoverished ichnological assemblage, and sporadic distribution of ichnogenera. Figure 5.6 illustrates the variation of ichnological character between prodelta and open-marine offshore deposits as seen in the Doe Creek Member. It is clear that the prodelta and open-marine offshore deposits of the Doe Creek Member display significant ichnological and sedimentological contrast. These findings are consistent with similar studies from the Permian sequences in the Denison Trough, eastern Australia (Bann and Fielding, 2004), the Dunvegan Formation (Gingras *et al.*, 1998; Coates and MacEachern, 1999), and the Bluesky Formation and Cadotte Member (Moslow and Pemberton, 1988). The unique characterization of prodeltaic deposits in the Doe Creek Member was instrumental to the accurate interpretation of facies and facies successions. Because wave-dominated and mixed river- and wave-influenced delta fronts can be very similar in appearance to open-marine shoreface successions, the identification of prodelta deposits coupled with the application of Walther's Law can be very helpful in determining the nature of ambiguous, shallow marine sandstones in the rock record.

CHAPTER SIX

CONCLUSIONS

1. The Doe Creek Member was deposited along the western margin of the Western Interior Seaway during the Late Cretaceous (Cenomanian) in northwest Alberta. The Doe Creek Sandstones are encased in predominantly marine mudstones of the Kaskapau Formation, which was deposited during a major eustatic transgression. The deposits of the Doe Creek Member comprise a series of retrogradationally-stacked, northeast-southwest trending, shorelines deposited during minor sea level falls and/or stillstands punctuating the overall transgression.
2. A detailed facies analysis was completed focusing on the integration of sedimentological and ichnological data, resulting in the identification of eleven facies. The facies represent deposits from shelf, offshore, prodelta, shoreface, delta front, channel, distributary mouth bar, and brackish bay environments. These were grouped into two facies associations based on recurring vertical succession of facies interpreted to reflect the progradation of an open-marine shoreface (FA1) and a prograding delta (FA2).
3. The sandstone bodies are consistent with those of mixed river- and wave-dominated delta fronts, deposited as lowstand deltas and/or shorefaces. Excellent core control along contemporaneous shorelines allowed for the evaluation of along-strike variation of facies within a single succession. The relationship of FA1 and FA2 was shown to be that of lateral equivalents along a spectrum of facies successions exhibiting degrees of deltaic influence corresponding to proximity to the riverine point source.
4. The Doe Creek Member comprises open-marine offshore deposits exhibiting an excellent representation of a fully-marine, unstressed *Cruziana* ichnofacies. The contrasts markedly with the ichnological assemblages noted in the prodeltaic facies. A model for the recognition of prodeltaic deposits was generated based on the data collected from the Doe Creek. This model can be of great use in identification of similar strata exhibiting ambiguous shallow marine sandstones, and in the identification of deltaic point sources along ancient coastal deposits.

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APPENDIX: CORE LITHOLOGS

The following appendix contains drafted lithologs for the 55 cored intervals of the Doe Creek Member logged for this study. The following page contains a legend of symbols used. The well location is given for each litholog, labeled at the top. Most of the lithologs are longer than a page, and thus are continued on successive pages. The following is a list of the well locations, and depths of the cored interval. The lithologs are presented in numerical order. An asterisk following the depths denotes an interval which required depth correction or there was insufficient data to verify, with certainty, the depths given.

1) 02-13-76-10W6 (680-692 m)
2) 06-02-76-08W6 (711.9-726.5 m)
3) 06-02-77-07W6 (488-506 m)
4) 06-03-73-08W6 (873-891 m)*
5) 06-05-77-07W6 (530-548 m)
6) 06-07-75-11W6 (790-808 m)*
7) 06-07-76-10W6 (665-679 m)
8) 06-09-73-10W6 (987-1004 m)
9) 06-13-76-11W6 (674-685 m)
10) 06-25-75-10W6 (704-722 m)
11) 02/06-30-73-10W6 (911-918 m)*
12) 06-30-73-12W6 (931-949.1 m)*
13) 06-36-74-10W6 (712-730 m)
14) 07-14-75-09W6 (712-721 m)
15) 07-25-74-11W6 (834-851 m)
16) 07-25-75-10W6 (673.6-691.3 m)*
17) 07-26-74-09W6 (735.5-772m)
18) 08-01-79-09W6 (301-314 m)
19) 08-09-73-12W6 (1006-1024.3 m)*
20) 08-10-75-12W6 (786-798.5 m)*
21) 08-16-75-08W6 (691-704 m)
22) 08-23-71-08W6 (1037-1055 m)
23) 08-26-75-11W6 (749.3-765 m)*
24) 08-30-75-11W5 (833.5-852 m)
25) 08-34-74-12W6 (788.6-805.5 m)*
26) 08-35-76-08W6 (564.6-580 m)*
27) 10-01-74-11W6 (897.7-922.3 m)*
28) 10-02-73-10W6 (957-968.4 m)
29) 10-23-72-11W6 (1077.5-1095.8m)*
30) 11-01-74-12W6 (903.6-928.6 m)*
31) 02/11-04-75-09W6 (702.7-717.1 m)*
32) 11-09-75-09W6 (696-723.2)
33) 11-33-71-12W6 (1210-1246.6 m)
34) 13-13-73-13W6 (986-1004 m)
35) 14-10-76-10W6 (706.5-724 m)
36) 14-11-75-12W6 (791.6-800 m)*
37) 14-24-75-10W6 (699-712.2 m)*
38) 14-25-73-13W6 (935-953.2 m)*
39) 14-25-74-12W6 (800-817.5 m)*
40) 14-27-73-13W6 (960.8-984.5 m)*
41) 14-30-77-06W6 (403-417.5 m)*
42) 14-31-74-10W6 (746-764 m)
43) 14-32-74-09W6 (678-701 m)
44) 14-34-74-09W6 (759-768 m)
45) 14-34-74-10W6 (697-715 m)
46) 14-35-74-10W6 (697-715 m)
47) 16-11-76-08W6 (640-658 m)
48) 16-11-76-11W6 (654.8-666.5 m)*
49) 16-12-73-11W6 (942-955.4 m)*
50) 16-22-75-08W6 (734-751.5 m)*
51) 16-28-77-13W6 (463-470.8 m)
52) 16-29-74-09W6 (704-725 m)*
53) 16-34-76-09W6 (657-675 m)
54) 16-35-74-09W6 (720-729.3 m)
55) 16-35-75-11W6 (703-720 m)

LEGEND

PHYSICAL STRUCTURES

- Current Ripples
- Swaley Cross-Strat.
- Low Angle Lamination
- Lenticular Bedding
- Convolute Bedding
- Normal Graded Bedding
- Double Mud Drapes
- Gutter Casts
- Trough Cross-Strat.
- Planar Tabular Bedding
- Oscillatory Ripples
- Wavy Parallel Lamination
- Bioturbated (Mottled)
- Micro-Fault
- Hummocky Cross-Strat.
- Load Casts

LITHOLOGIC ACCESSORIES

- Sand Lamina
- Pebbles/Granules
- Organic Shale Lamina
- Shale Lamina
- Coal Fragments
- Rip Up Clasts
- Syneresis Cracks
- Sid Siderite
- Wd Wood Fragments
- Py Pyrite
- Shell Fragments
- Sid Siderite Nodule
- Calcareous

ICHNOFOSSILS

- Rootlets
- Planolites
- Diplocraterion
- Ophiomorpha
- Rhizocorallium
- Conichnus
- Asterosoma
- Chondrites
- Zoophycos
- Cylindrichnus
- Siphonichnus
- Rosselia
- Crypt Cryptic Bioturbation
- Schaubcylindrichnus freyi
- Lockeia
- Phycosiphon
- Macaronichnus
- Scolicia
- Helminthopsis
- Bergaueria
- Thalassinoides
- Teichichnus
- Fugichnia
- Skolithos
- Palaeophycus
- Arenicolites
- Spirophyton

LITHOLOGY

- Sandstone
- Silty Sand
- Shaly Sand
- Silt/Siltstone
- Sandy Siltstone
- Shaly Siltstone
- Shale/Mudstone
- Silty Mudstone
- Sandy Mudstone
- Claystone
- Organic Shale
- ☒ Lost Core

BIOTURBATION

- ■ Abundant
- ■ Common
- ■ Moderate
- □ Rare
- ▩ Barren

CONTACTS

- Sharp
- Erosional
- Bioturbated
- Firmground

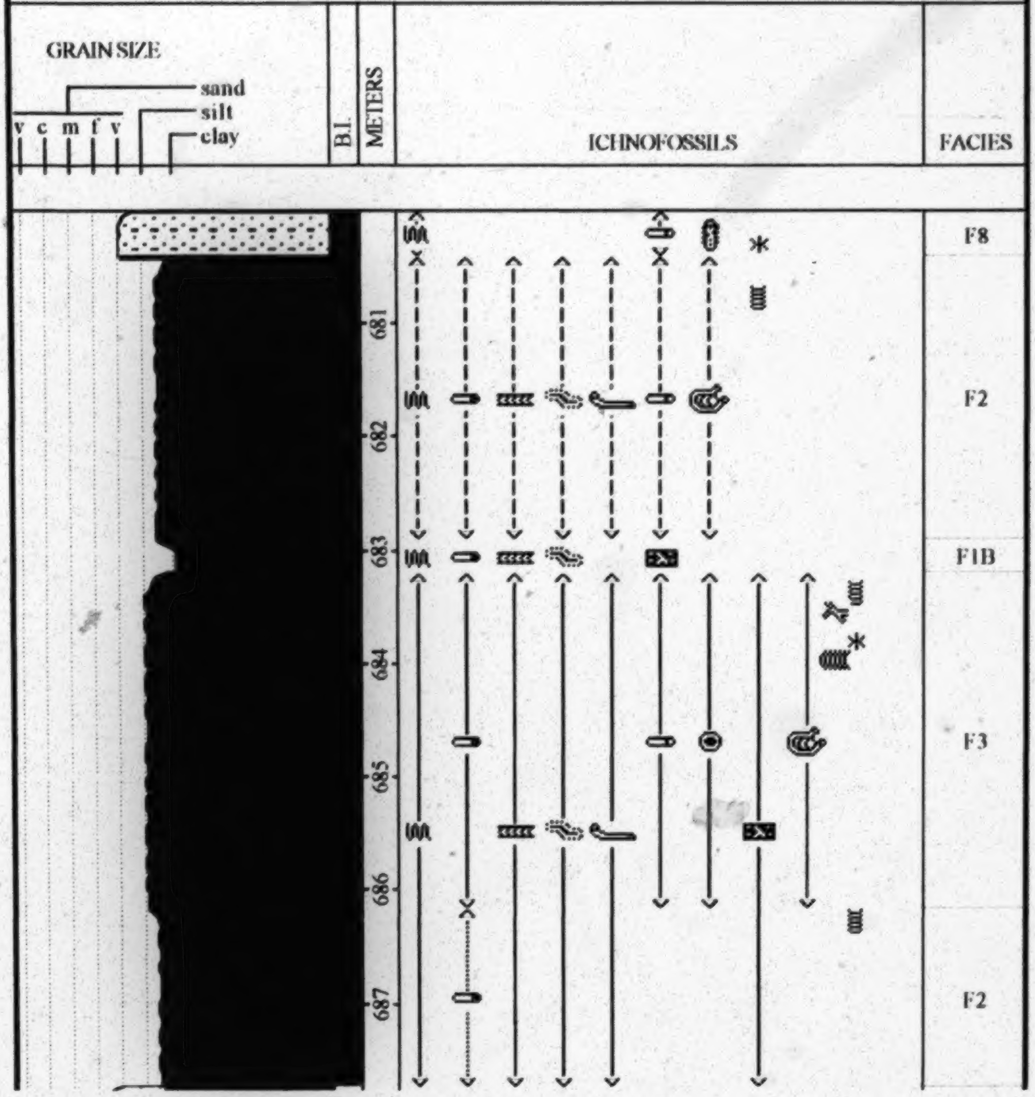
02-13-76-10w6

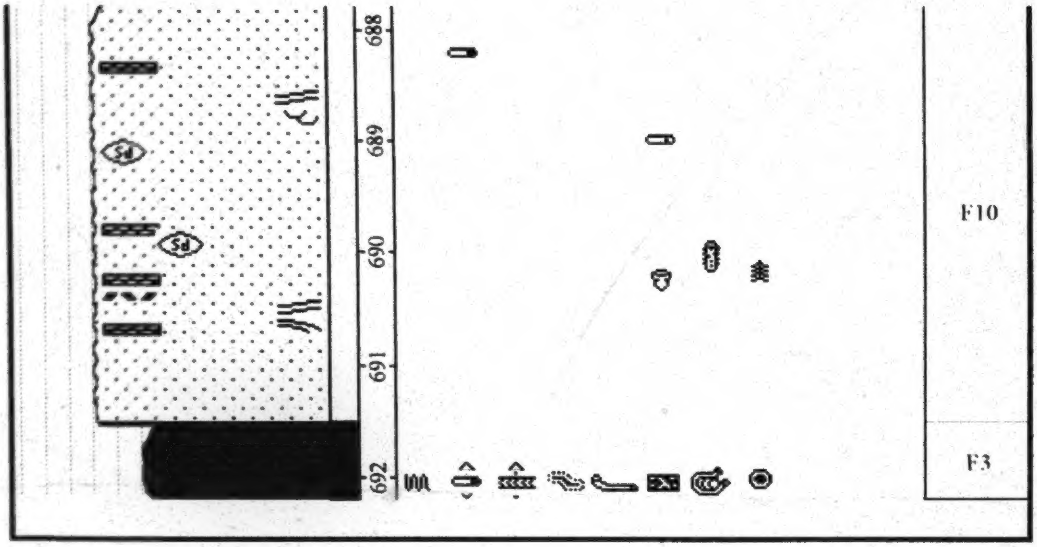
Date Logged: June 25, 2003

Logged by: © 2005 Scott A. Reid

Ground: 890.40 m KB: 894.00 m

I.R.G.
Ichnology Research Group





688
689
690
691
692
Sd
Sd
F10
F3

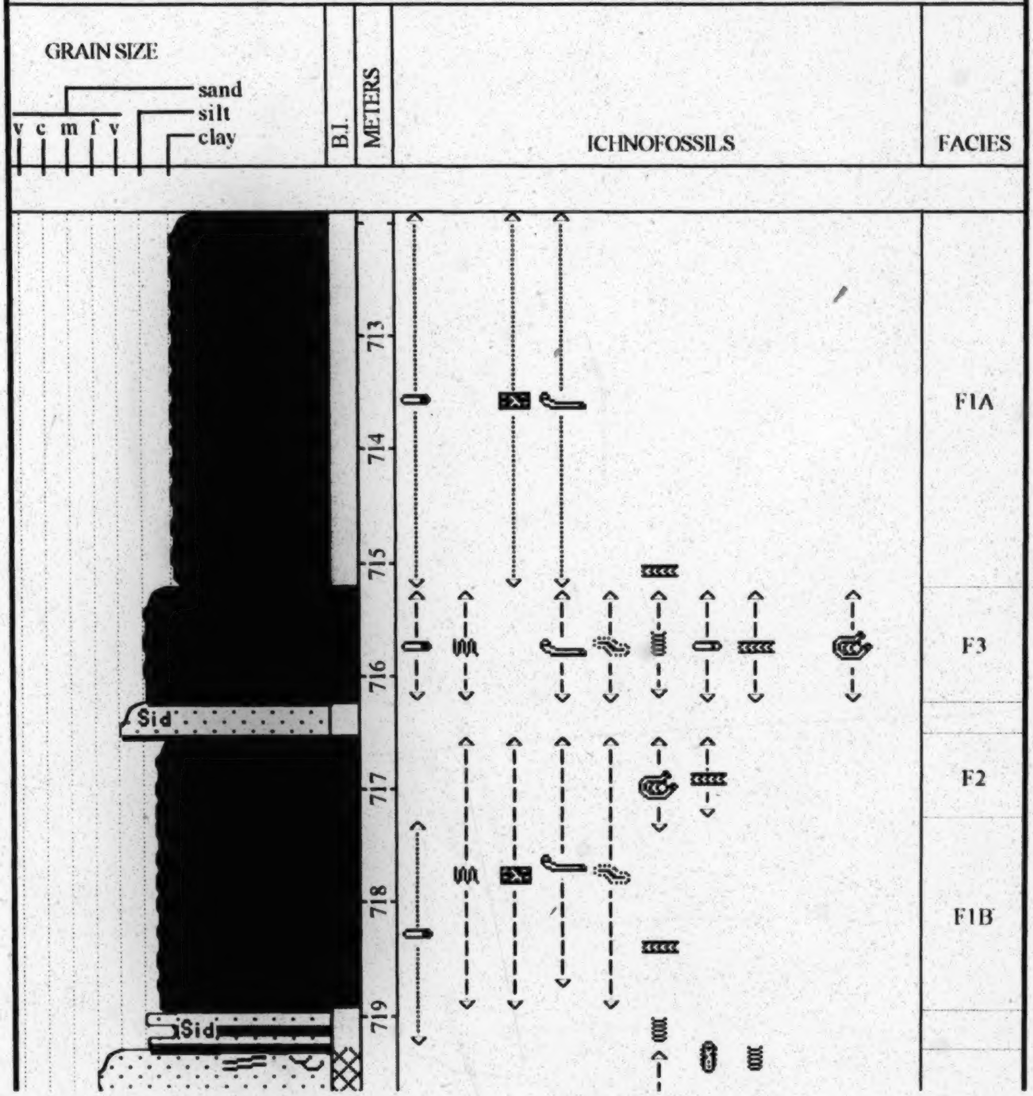
06-02-76-8w6

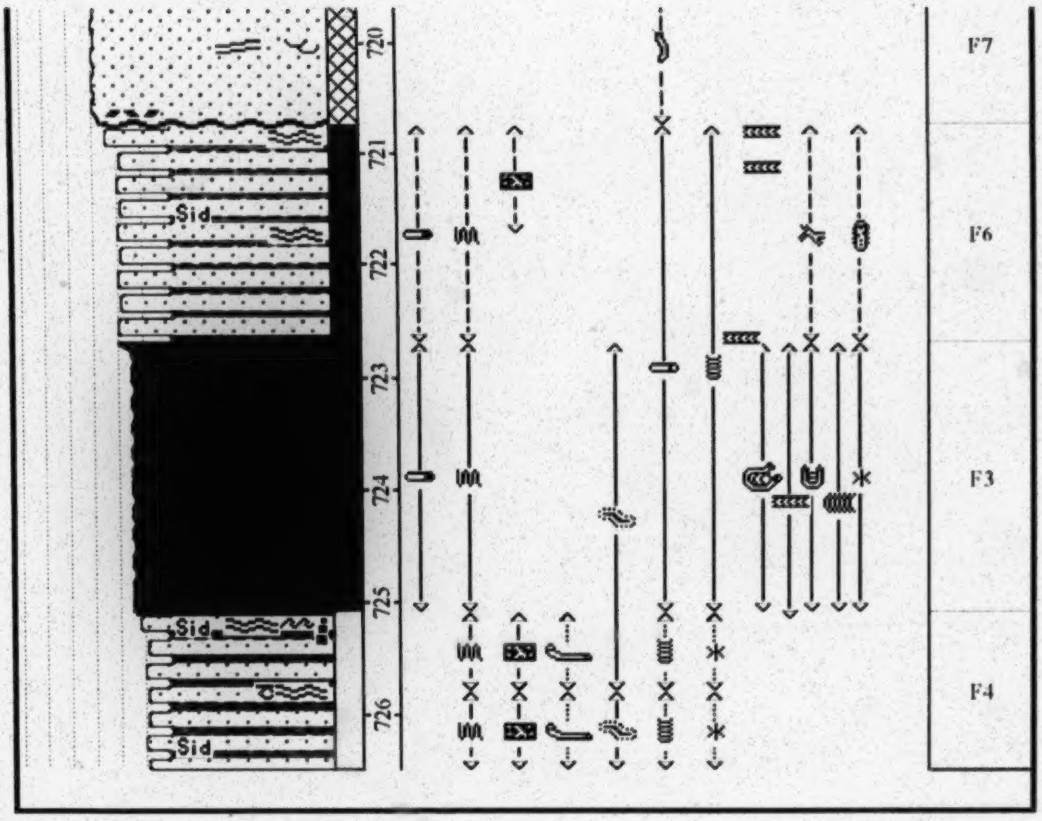
Date Logged: June 16, 2003

Logged by: © 2005 Scott A. Reid

Ground: 898.80 m KB: 902.30 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
713
714
715
716
717
718
719
Sid
Sid
F1A
F3
F2
F1B


720
721
722
723
724
725
726
Sid
Sid
Sid
F7
F6
F3
F4

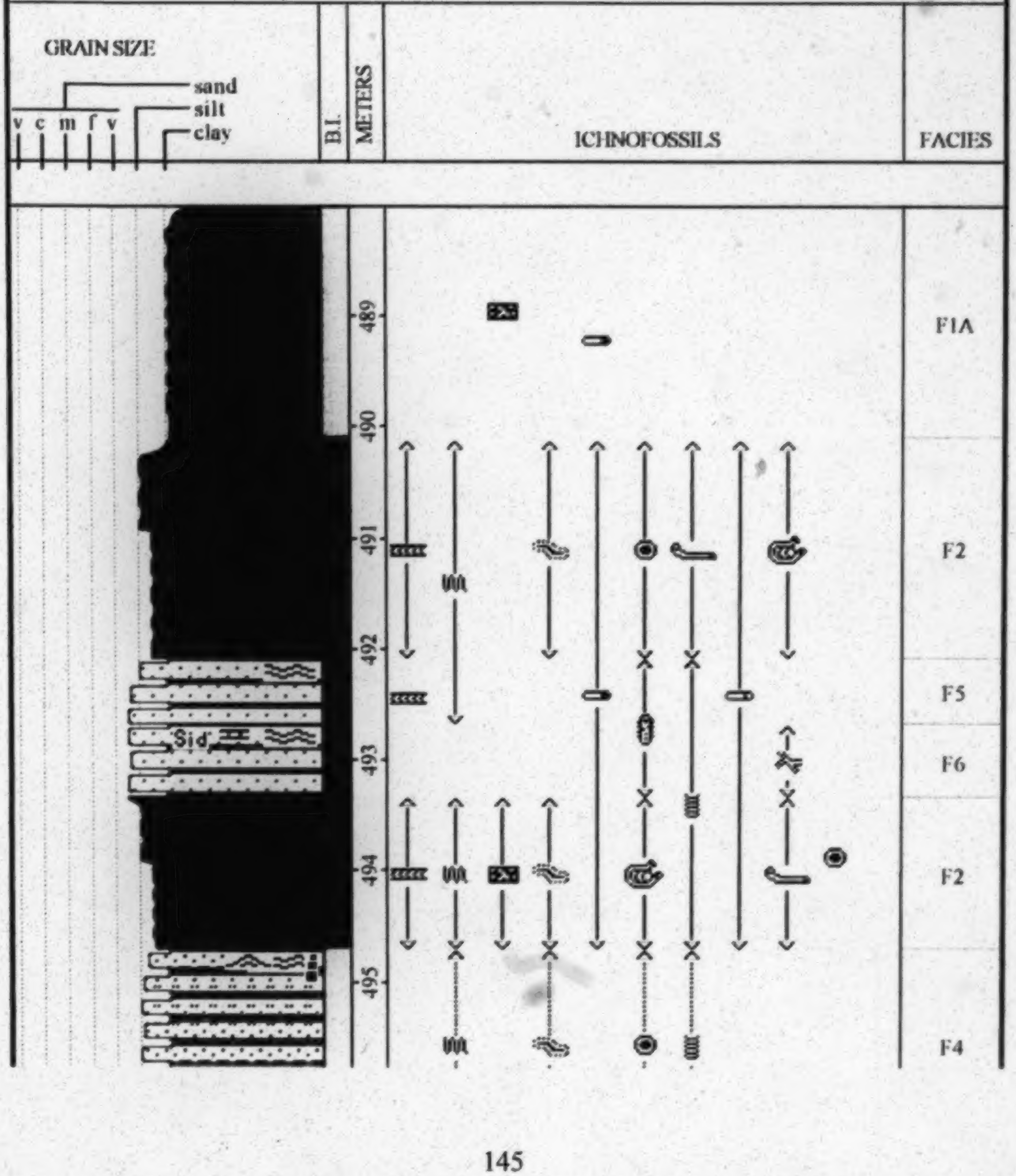
06-02-77-7w6

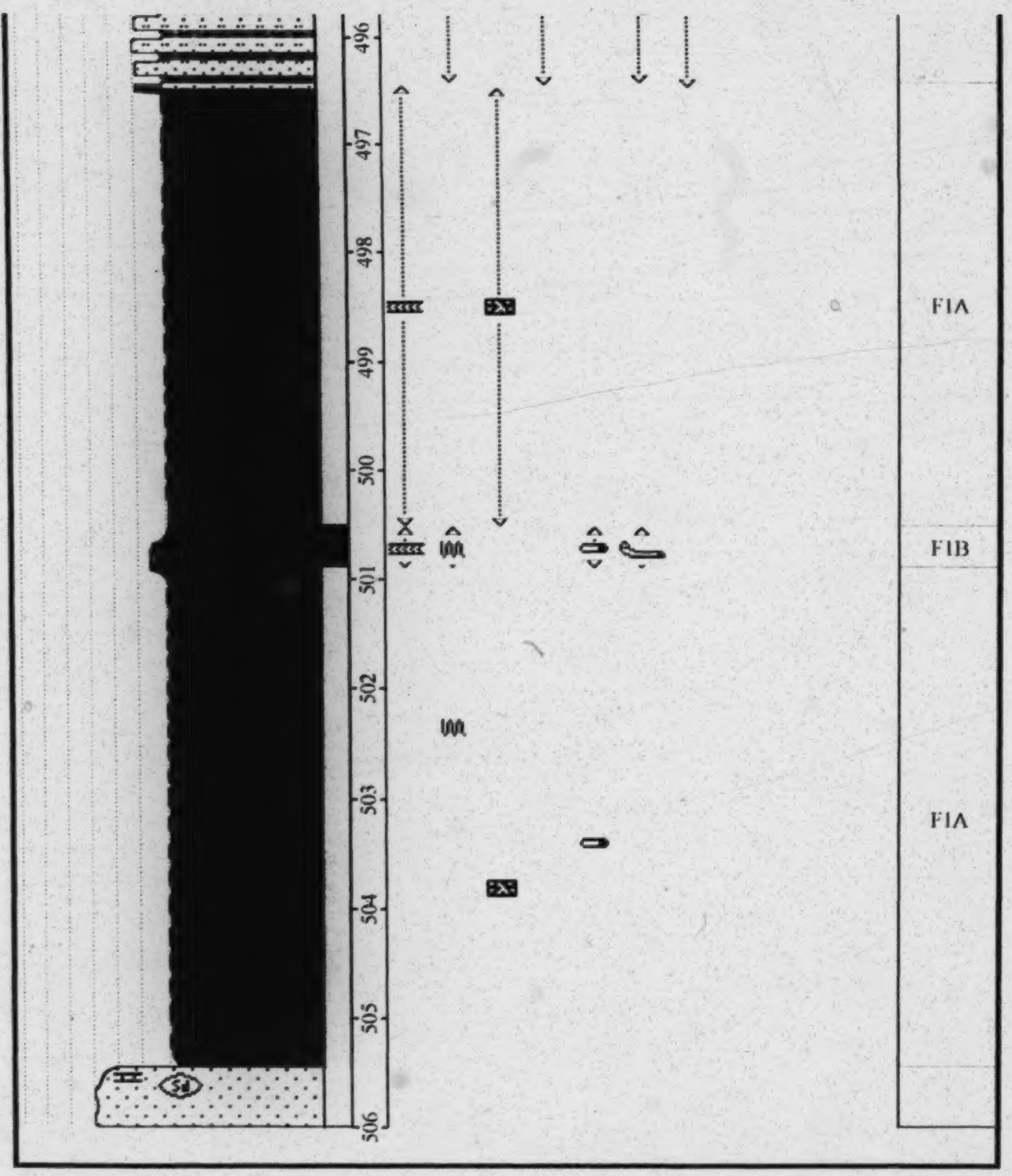
Date Logged: June 24, 2003

Logged by: © 2005 Scott Reid

Ground: 762.70 m KB: 765.30 m

I.R.G. Ichnology Research Group

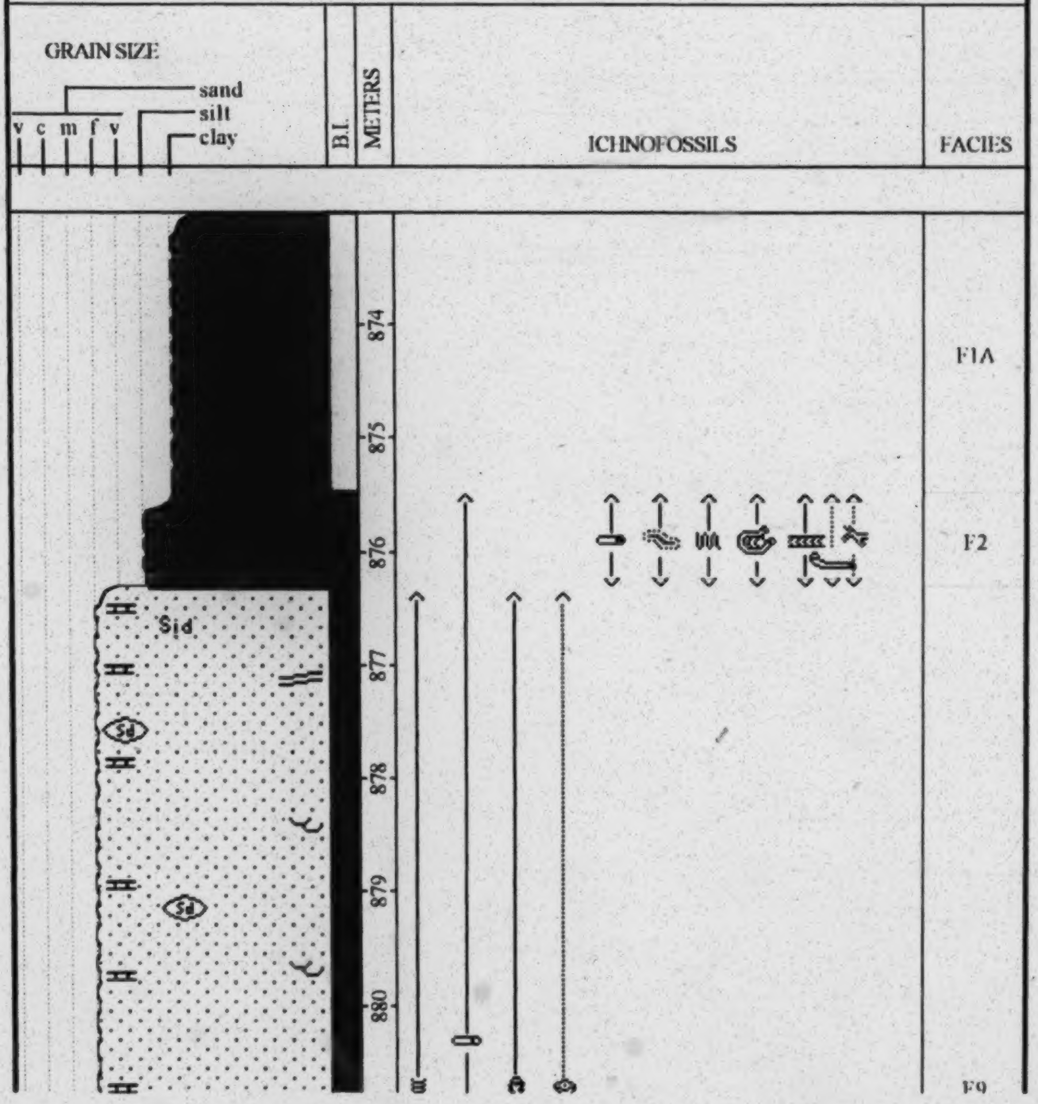

GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
489
490
491
492
493
494
495
Sid
F1A
F2
F5
F6
F2
F4

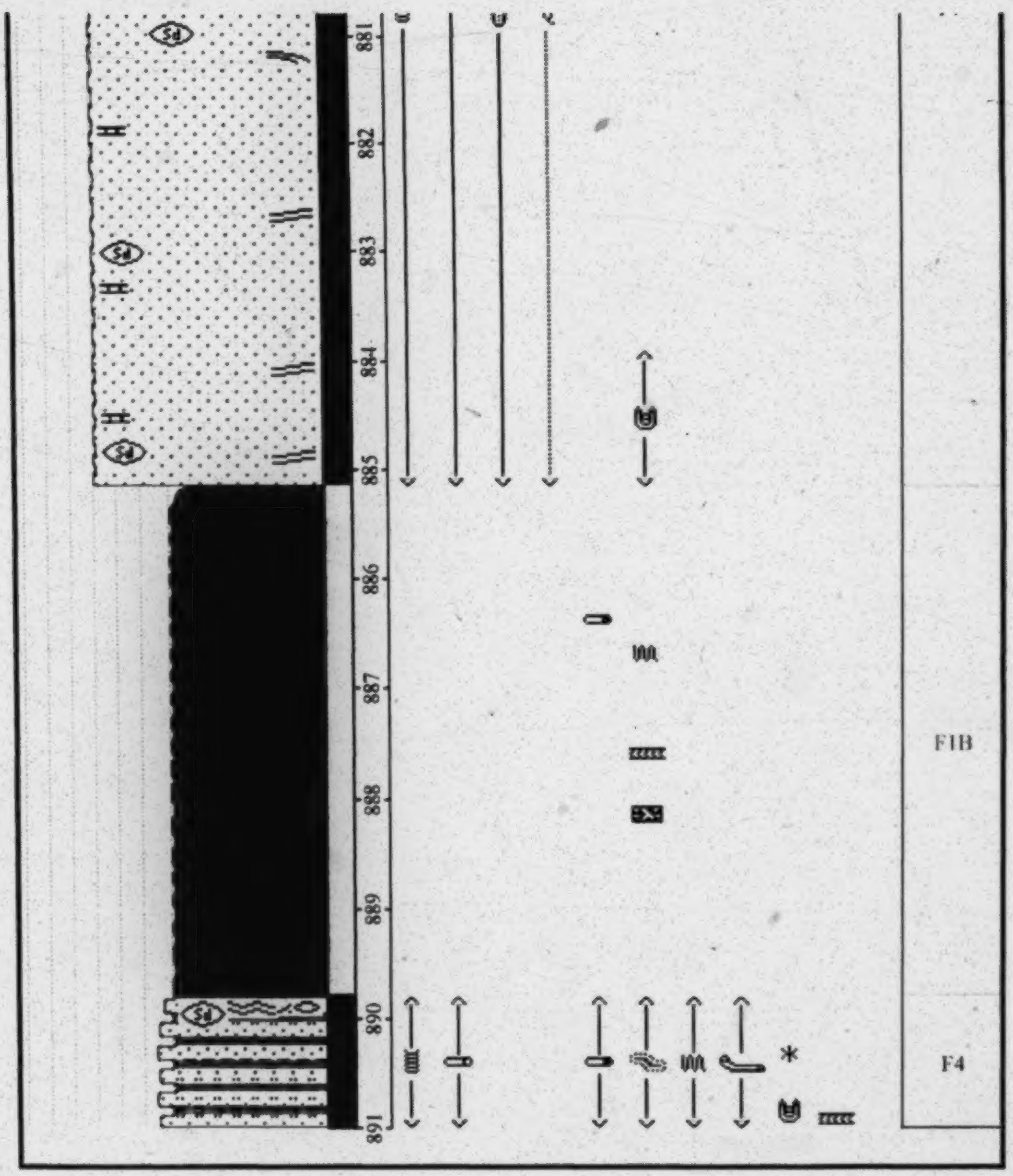

F1A
F1B
F1A

06-03-73-8w6

Date Logged: July 31, 2003
Logged by: © 2005 Scott A. Reid
Ground: 707.70 m KB: 712.70 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
874
875
876
877
878
879
880
Sid
Sd
Sd
F1A
F2
F0

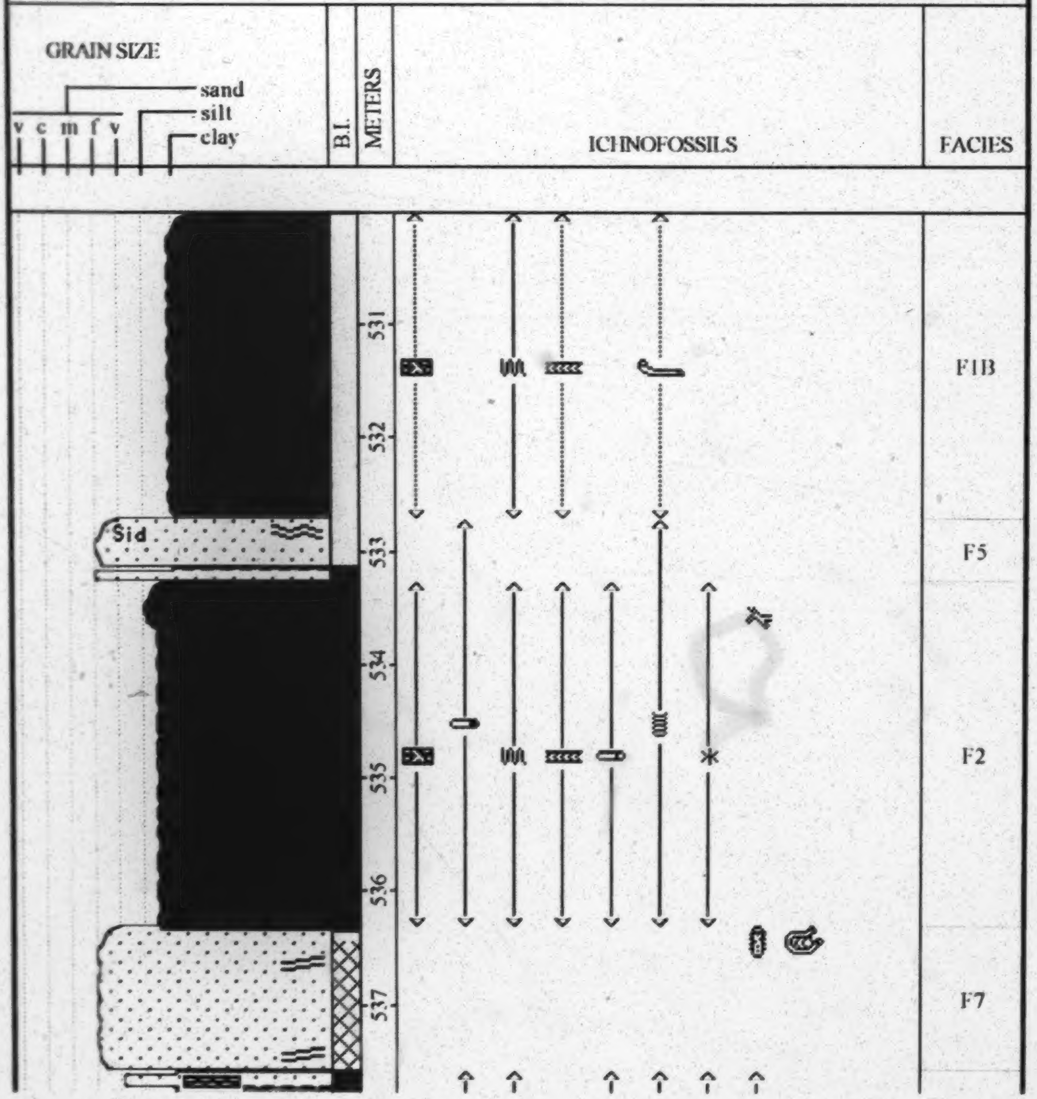

F1B
F4

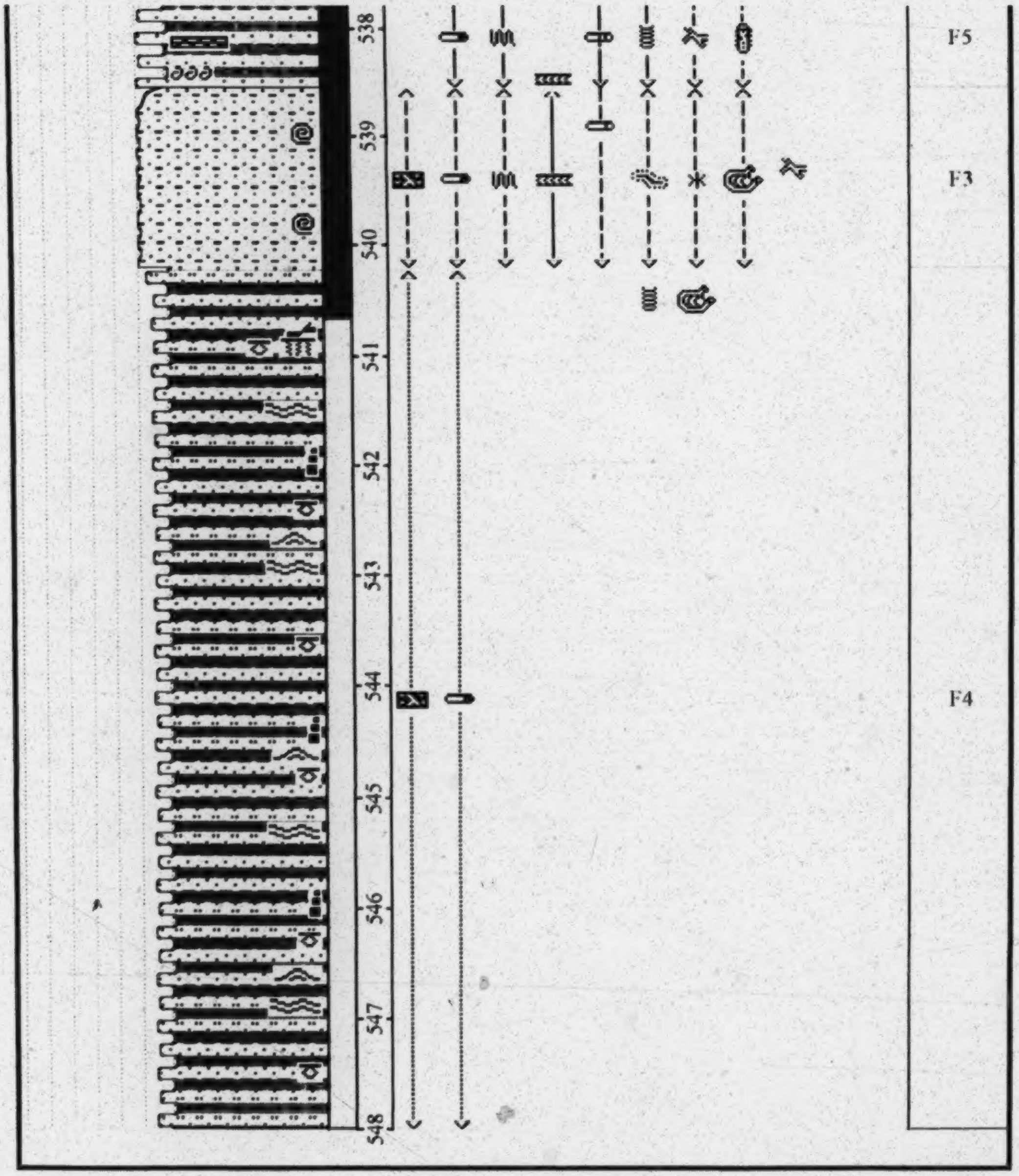
06-05-77-7w6

Date Logged: June 19, 2003

Logged by: © 2005 Scott A. Reid

Ground: 800.80 m KB: 803.90 m


GRAIN SIZE
v c m f v
sand
silt
clay
B.I.
METERS
ICHNOFOSSILS
FACIES
Sid
531
532
533
534
535
536
537
F1B
F5
F2
F7


F5
F3
F4

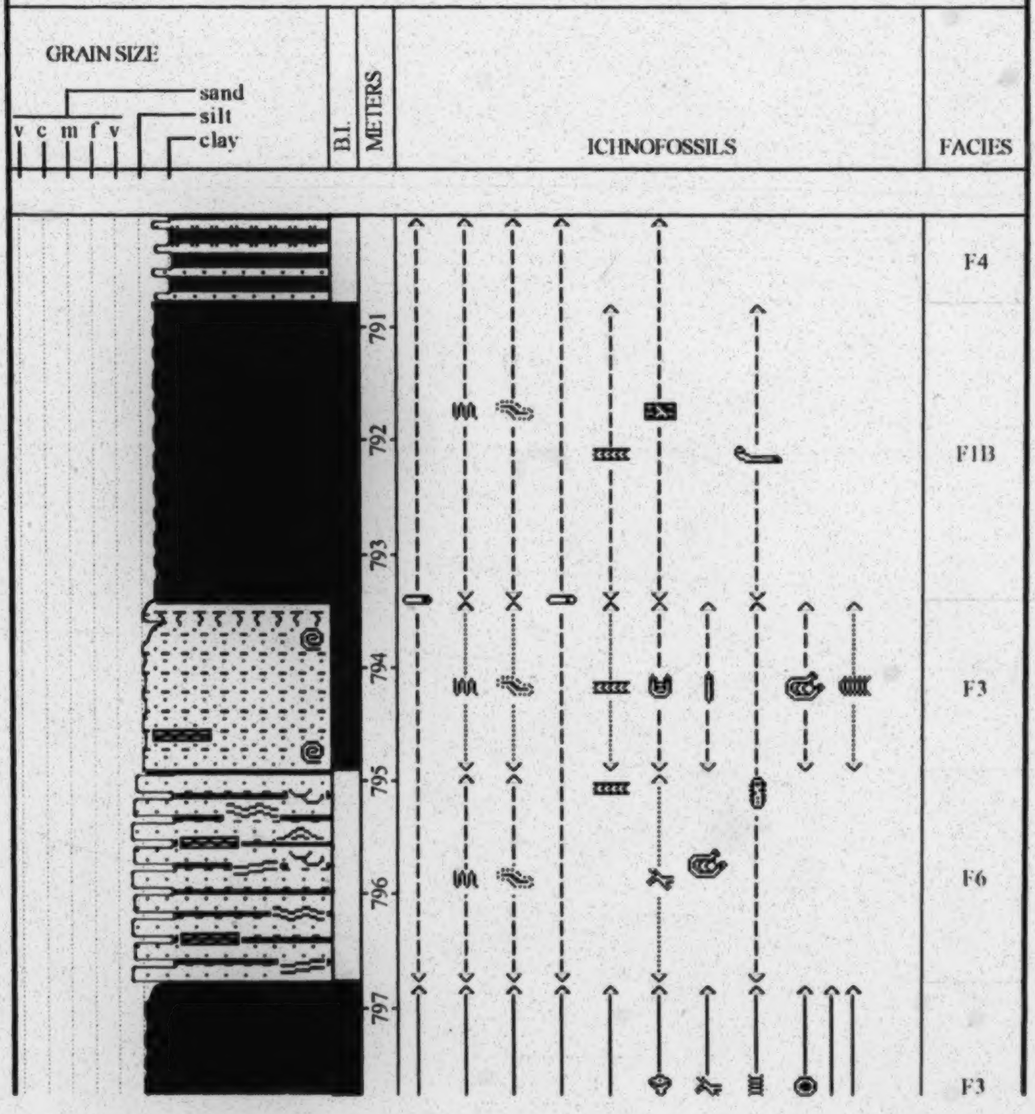
06-07-75-11w6

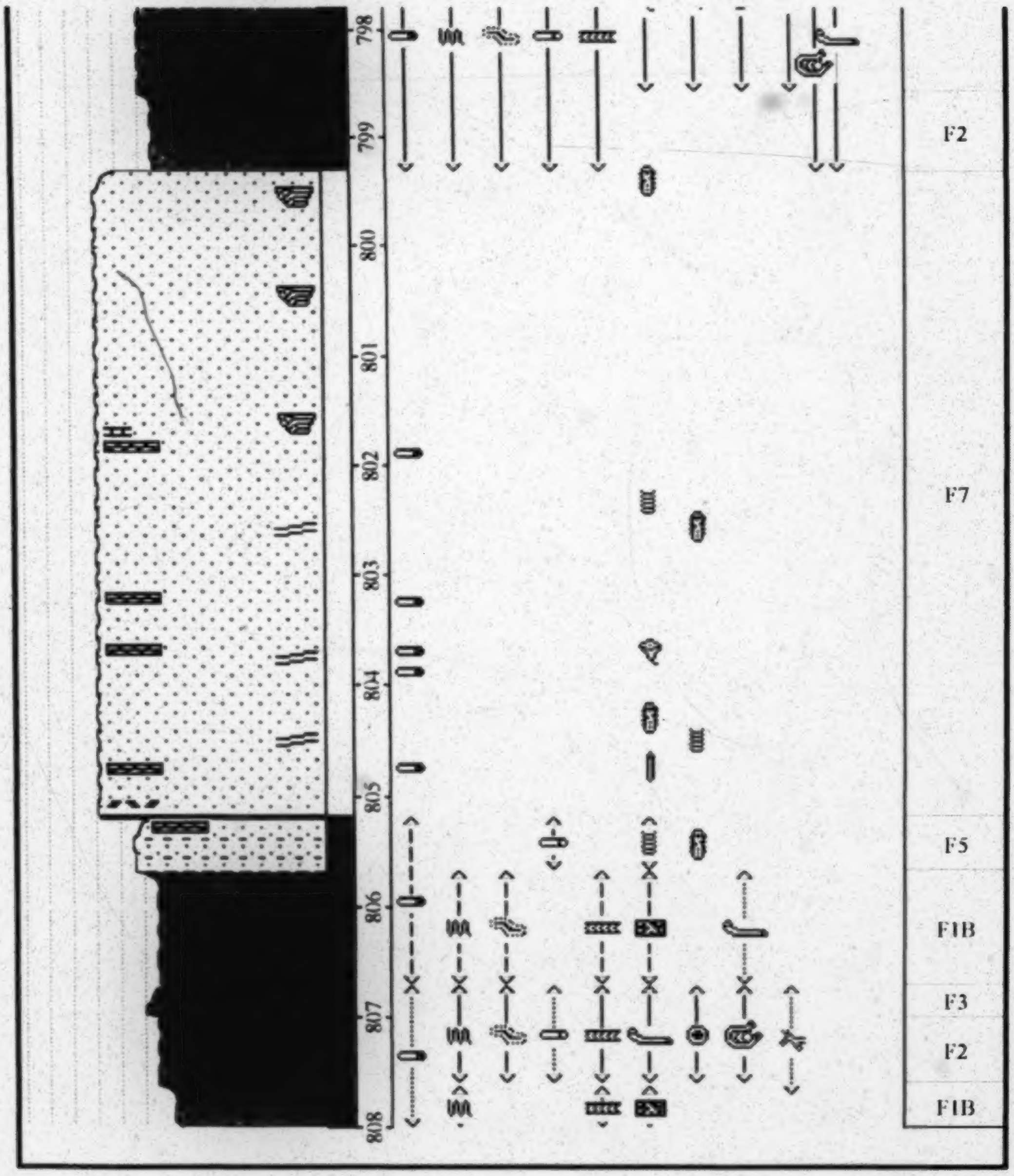
Date Logged: July 16, 2003

Logged by: © 2005 Scott A. Reid

Ground: 847.50 m KB: 850.60 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
791
792
793
794
795
796
797
F4
F1B
F3
F6
F3


F2
F7
F5
F1B
F3
F2
F1B

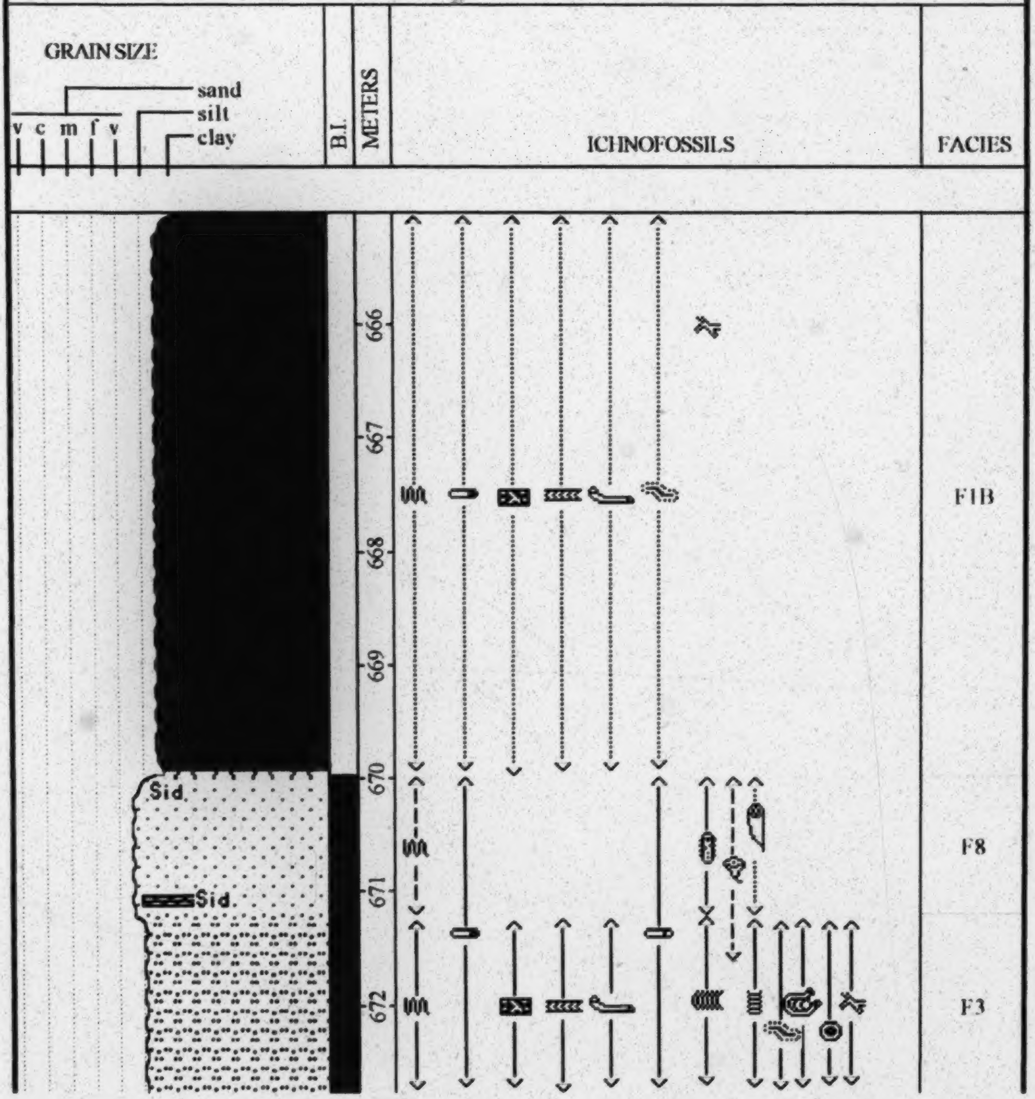
06-07-76-10w6

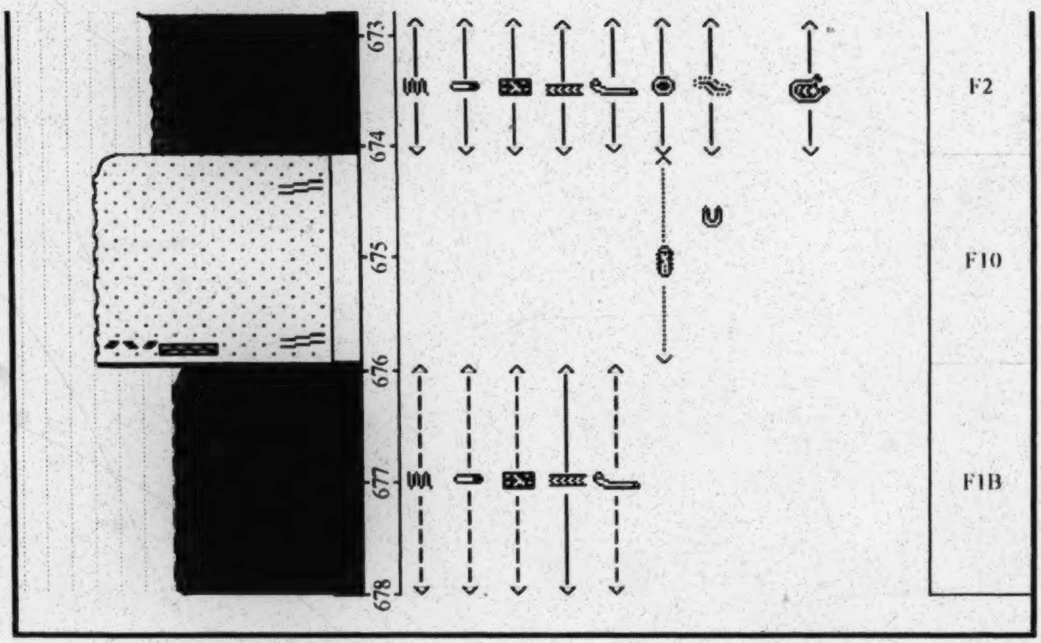
Date Logged: July 7, 2003

Logged by: © 2005 Scott Reid

Ground: 850.80 m KB: 853.80 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
666
667
668
669
670
671
672
Sid.
Sid.
F1B
F8
F3

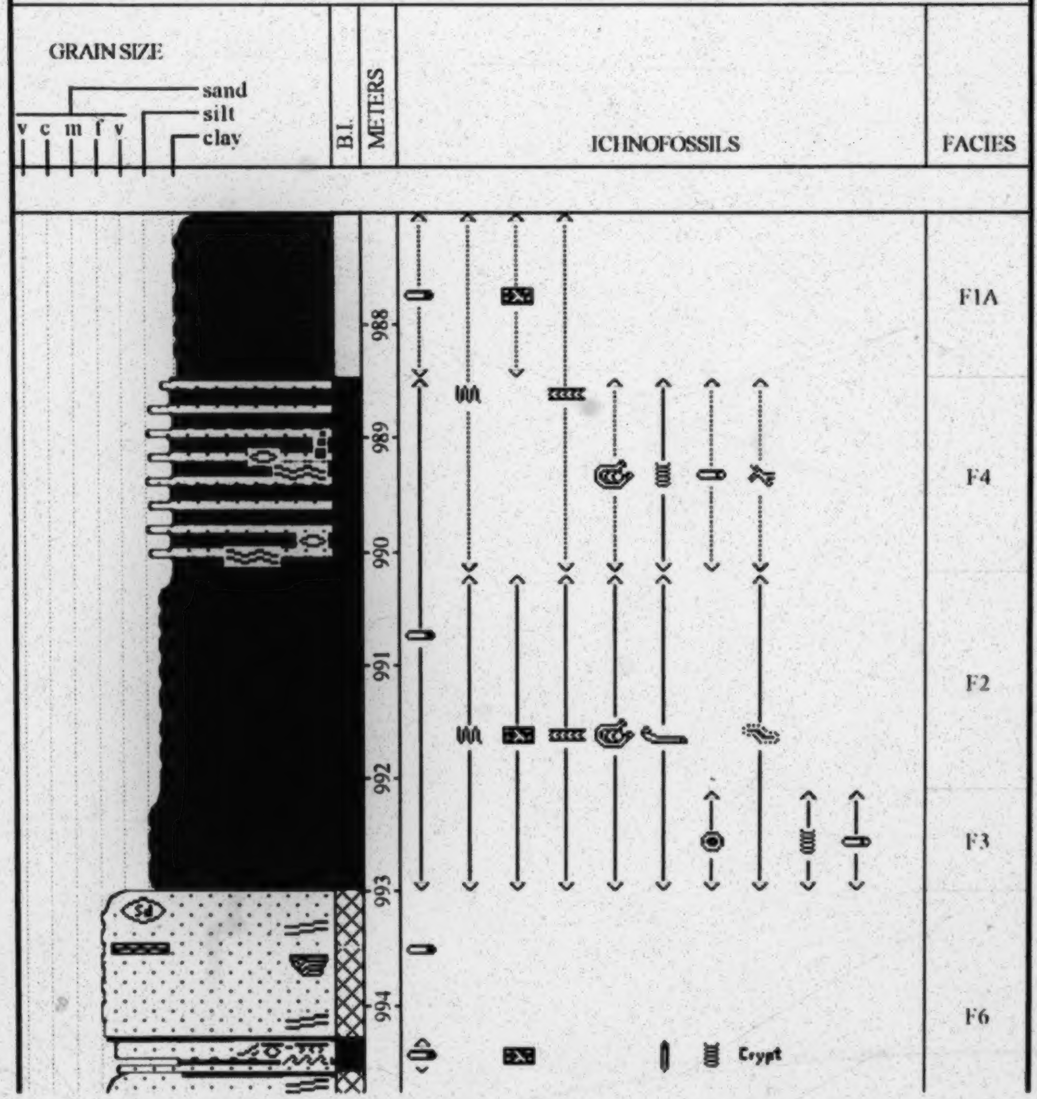

F2
F10
F1B

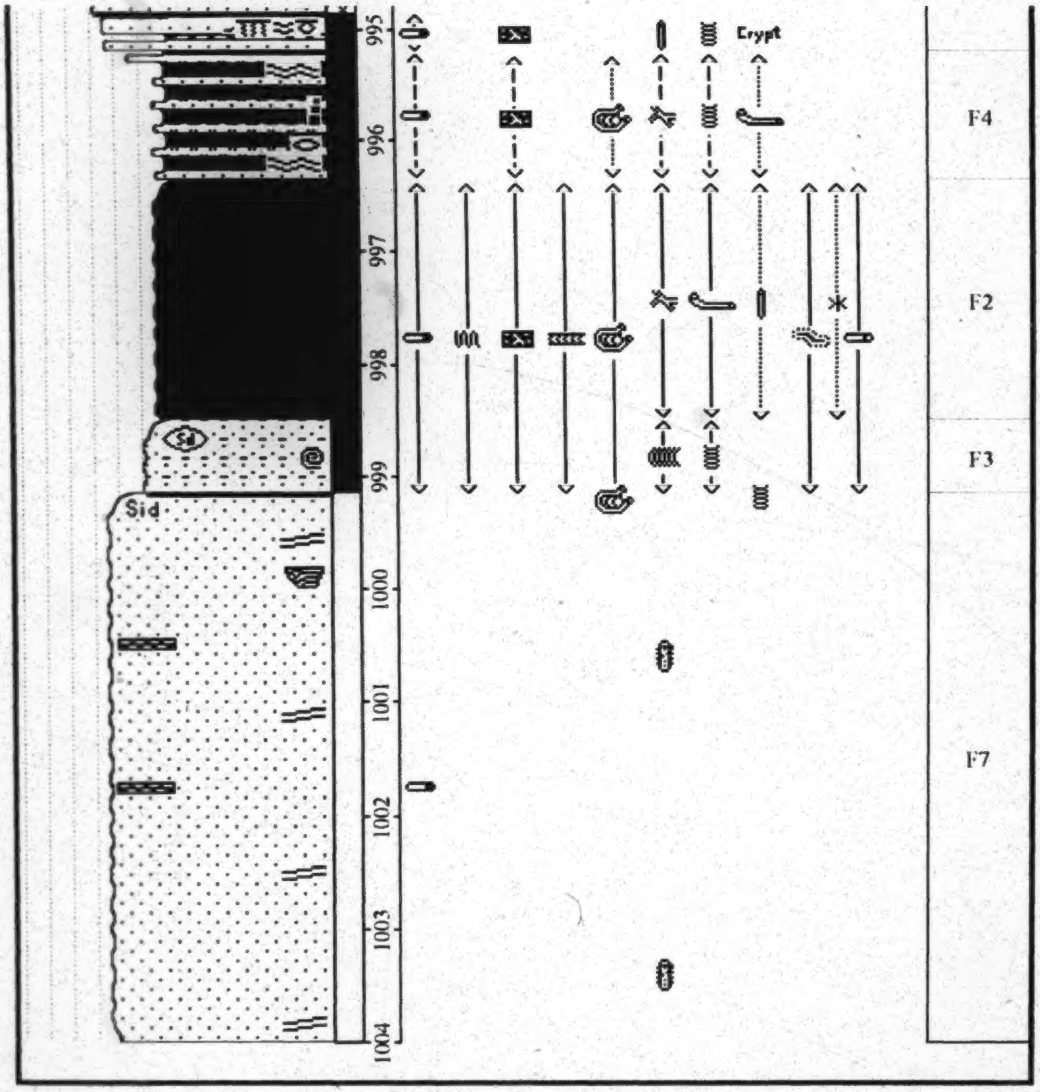
06-09-73-10w6

Date Logged: June 10, 2004

Logged by: © 2005 Scott A. Reid

Ground: 785.80 m KB: 789.90 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
988
989
990
991
992
993
994
F1A
F4
F2
F3
F6
Crypt


Sid
Crypt
F4
F2
F3
F7

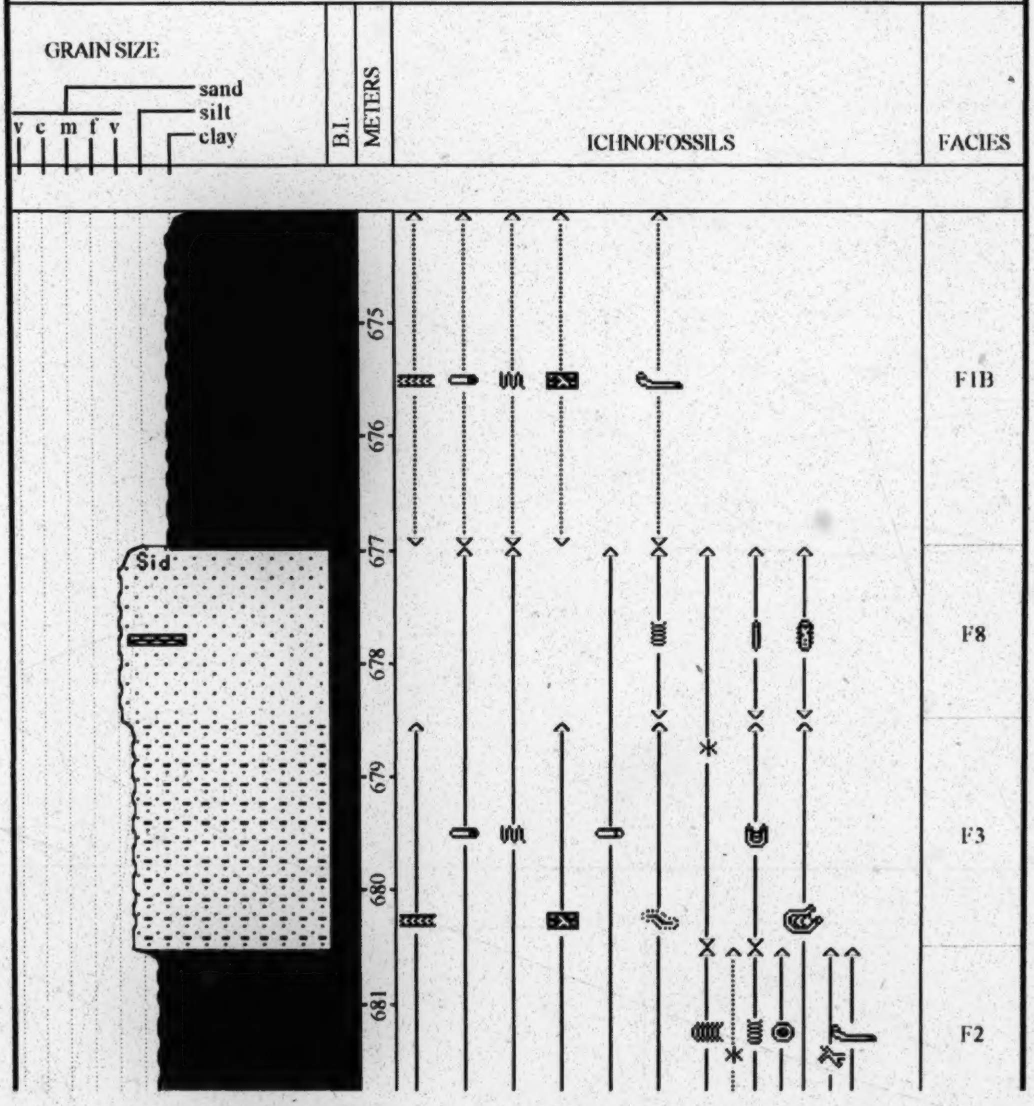
06-13-76-11w6

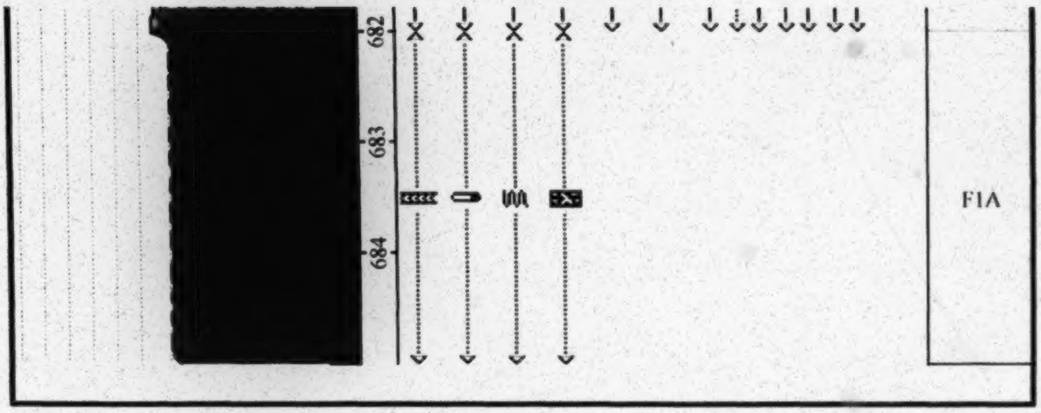
Date Logged: July 8, 2003

Logged by: © 2005 Scott A. Reid

Ground: 873.10 m KB: 876.10 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
675
676
677
678
679
680
681
Sid
F1B
F8
F3
F2


682
683
684
FIA

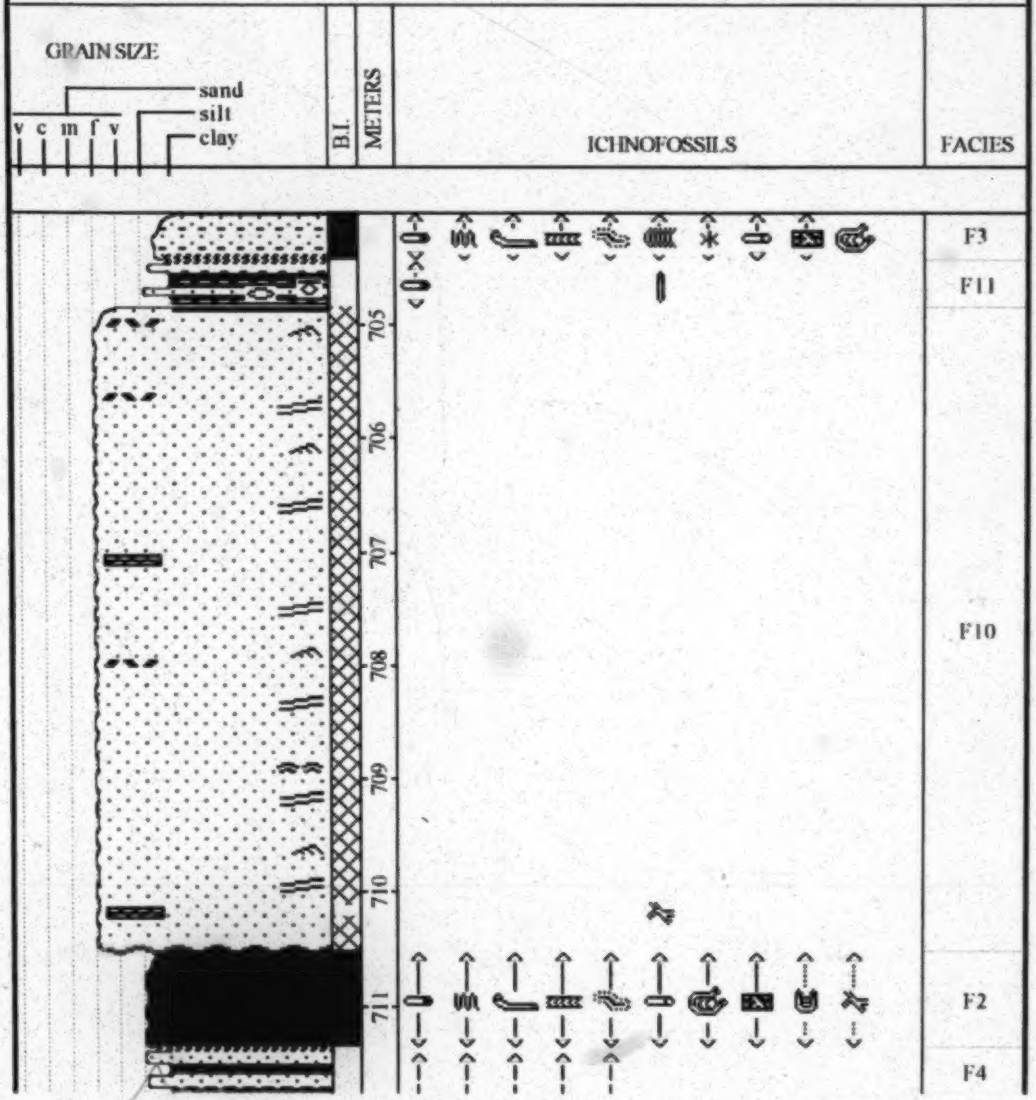
06-25-75-10w6

Date Logged: July 8, 2003

Logged by: © 2005 Scott A. Reid

Ground: 827.10 m KB: 830.10 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
705
706
707
708
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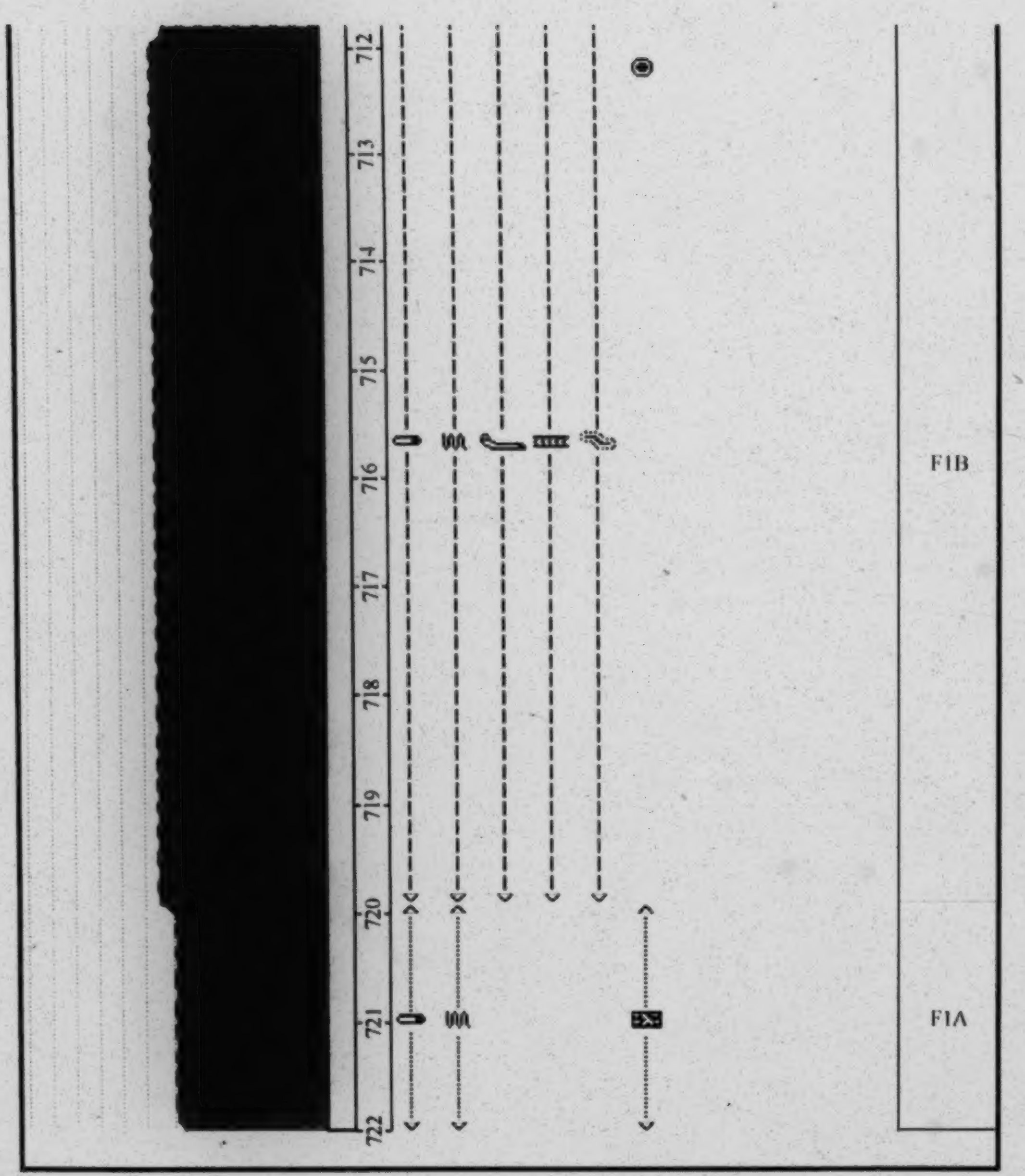
710
711
F3
F11
F10
F2
F4


712
713
714
715
716
717
718
719
720
721
722
F1B
F1A

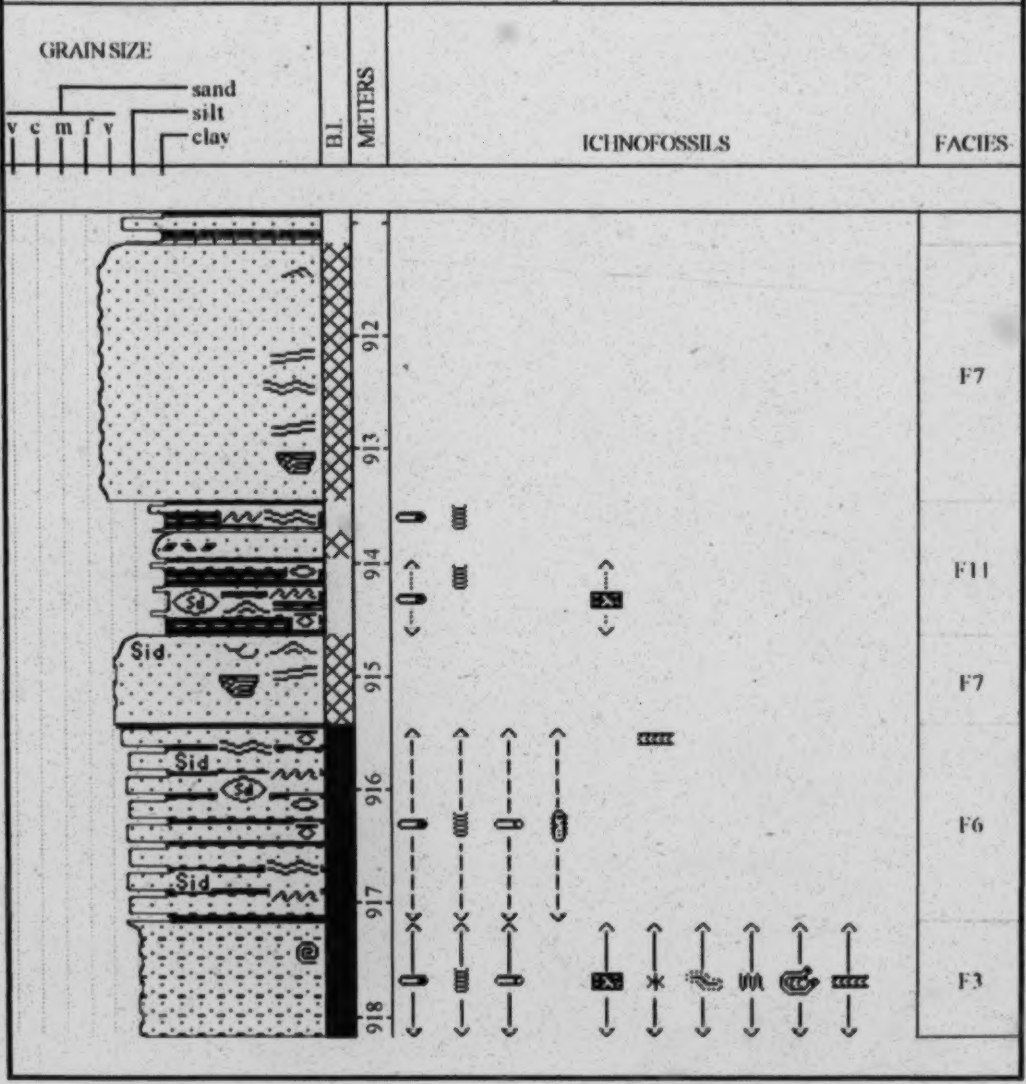
06-30-73-10w6

Date Logged: August 5, 2003

Logged by: © 2005 Scott A. Reid

Ground: 754.90 m KB: 758.00 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
912
913
914
915
916
917
918
Sid
Sd
F7
F11
F7
F6
F3

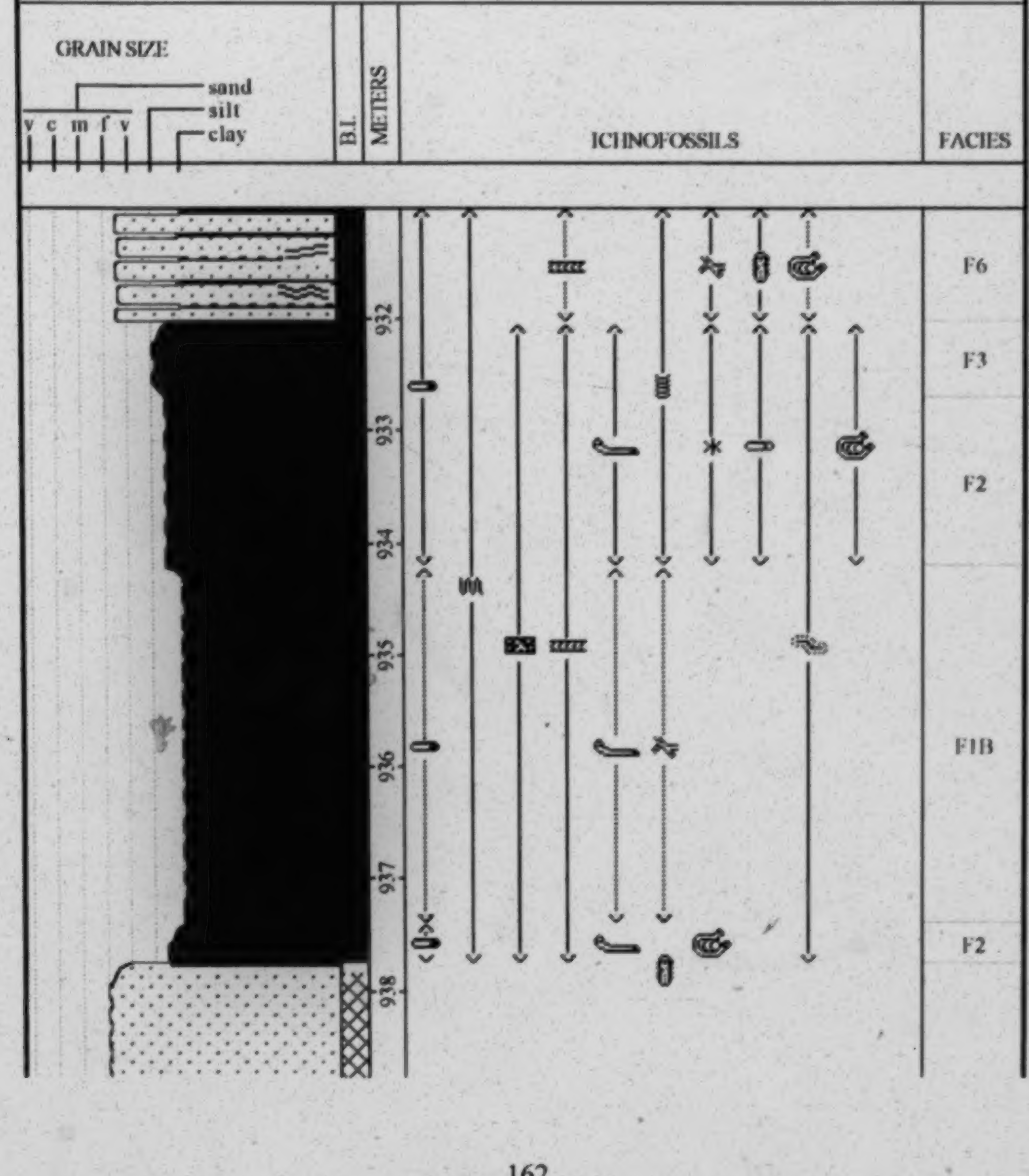
06-30-73-12w6

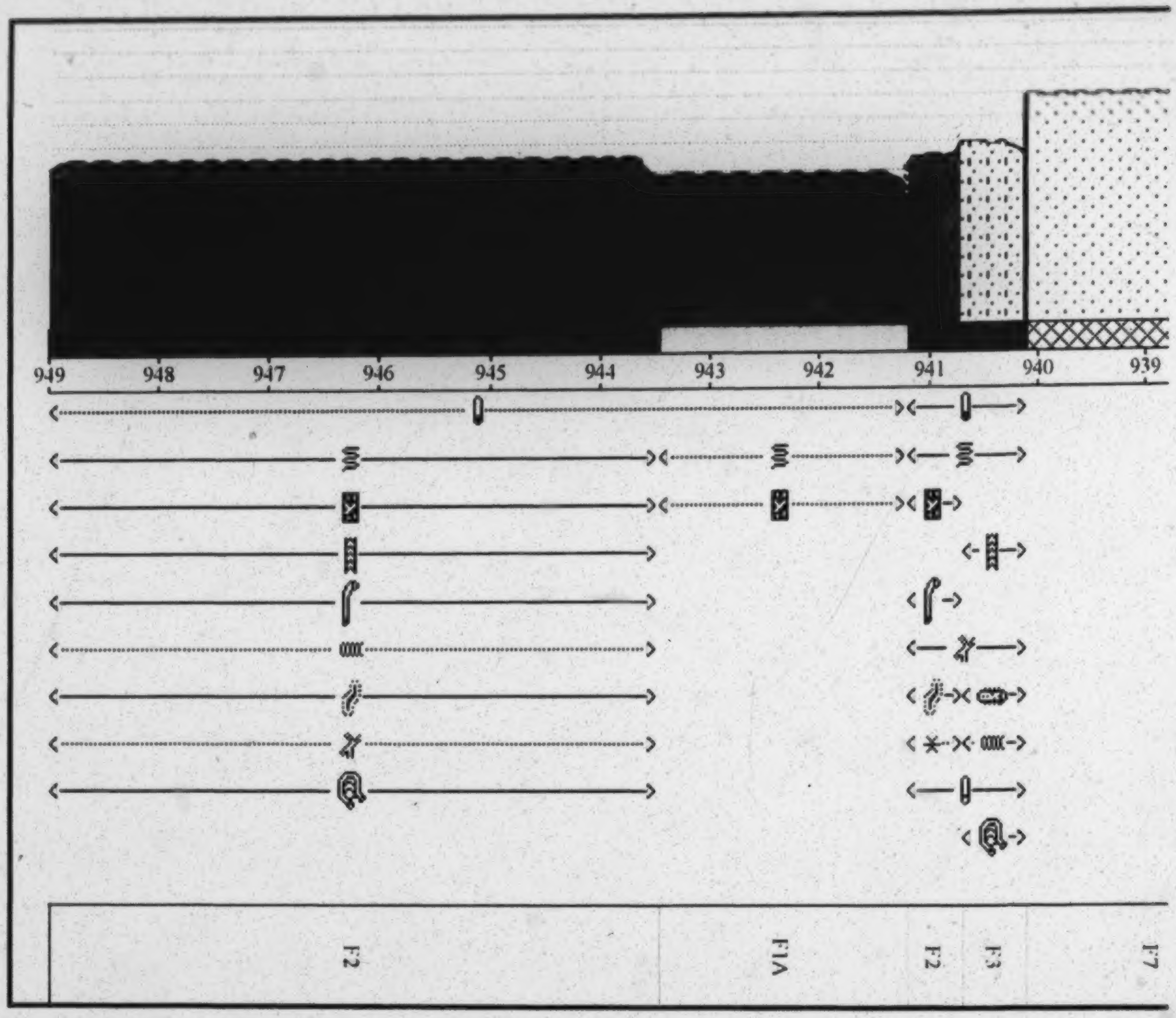
Date Logged: June 14, 2004

Logged by: © 2005 Scott A. Reid

Ground: 781.00 m   KB: 784.90 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
932
933
934
935
936
937
938
F6
F3
F2
F1B
F2

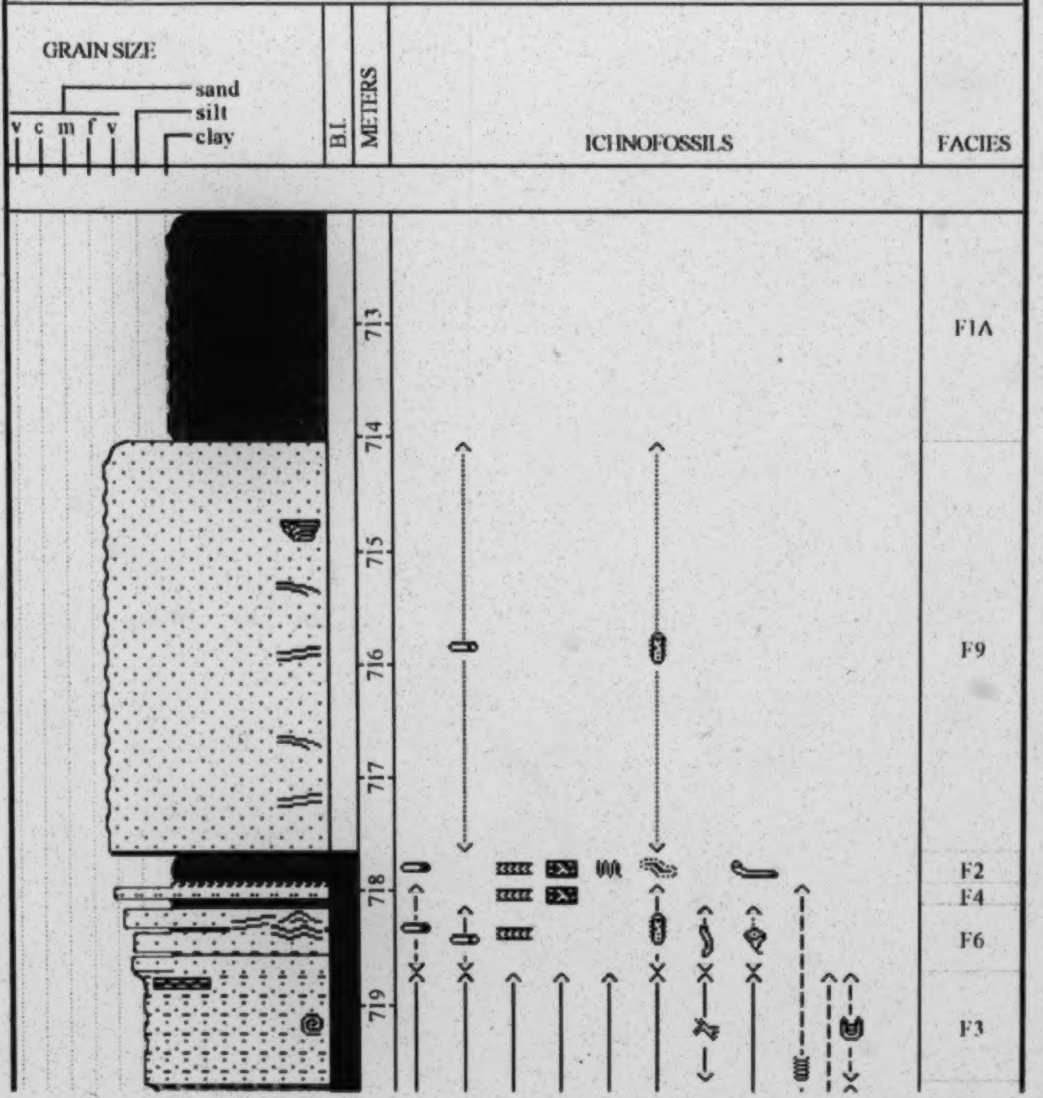

F2
F1A
F2
F3
F7

06-36-74-10w6

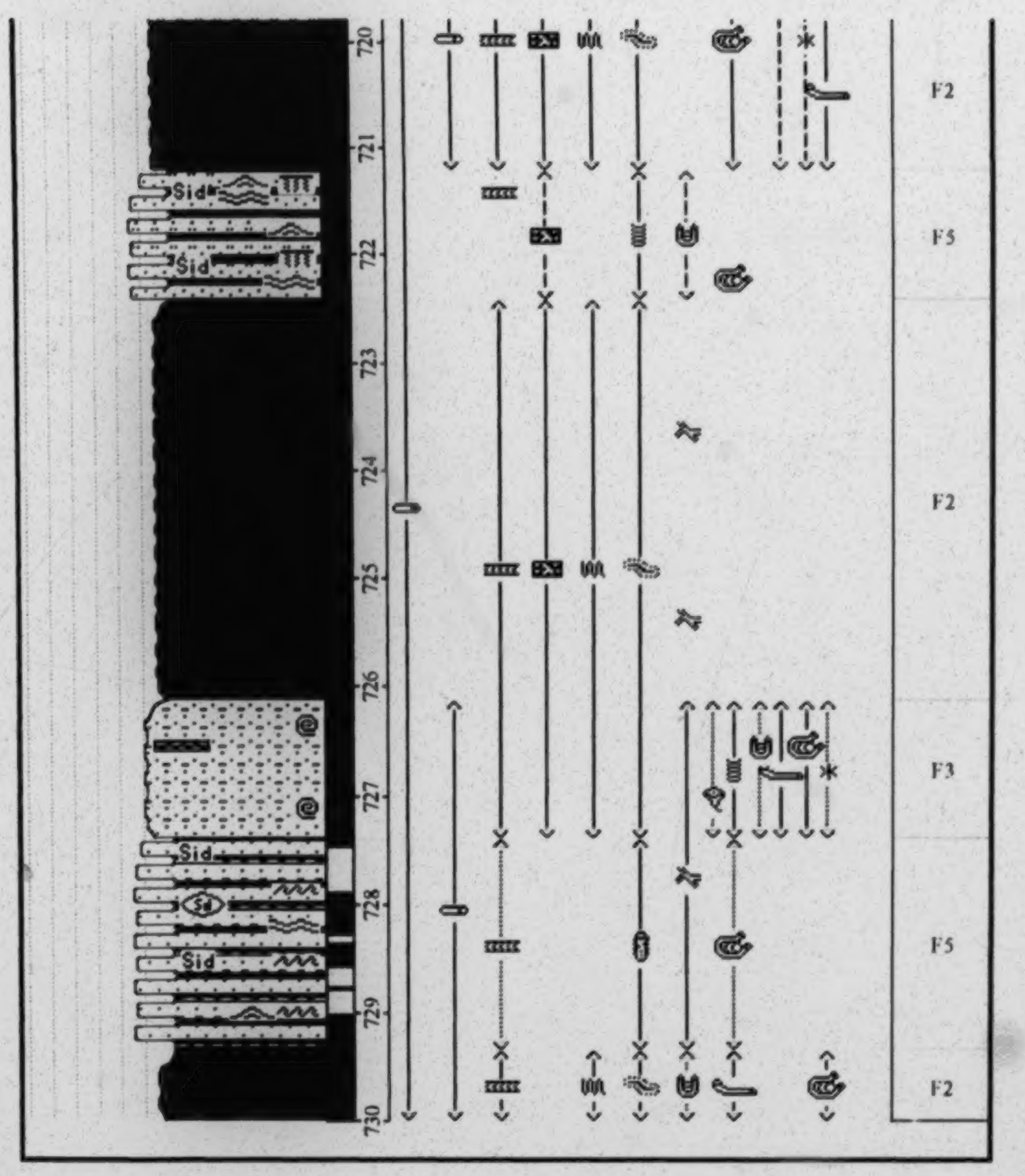
Date Logged: August 11, 2003

Logged by: © 2005 Scott A. Reid

Ground: 758.60 m KB: 761.40 m



GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
713
714
715
716
717
718
719
F1A
F9
F2
F4
F6
F3


720
721
722
723
724
725
726
727
728
729
730
Sid
Sid
Sid
Sd
Sid
F2
F5
F2
F3
F5
F2

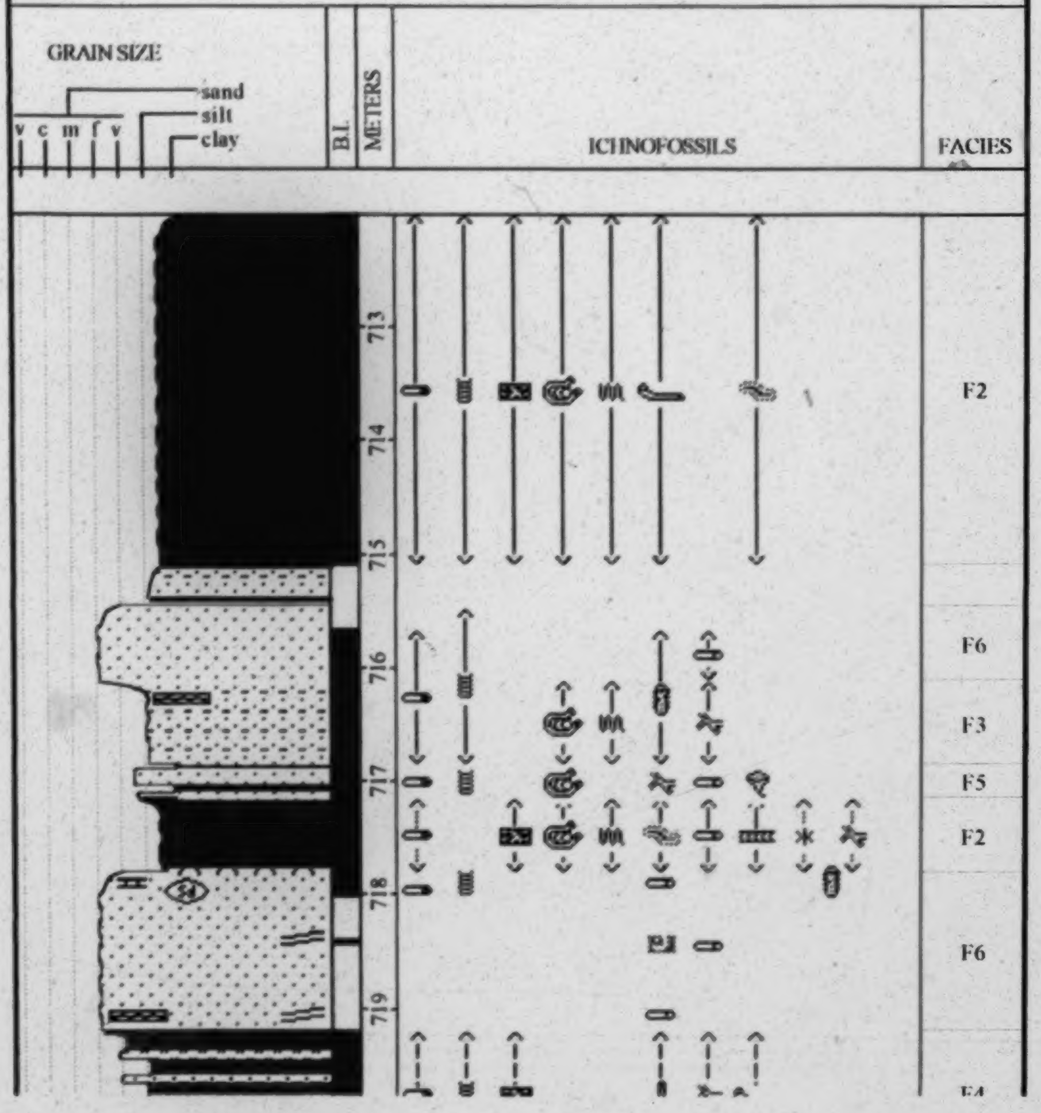
07-14-75-9w6

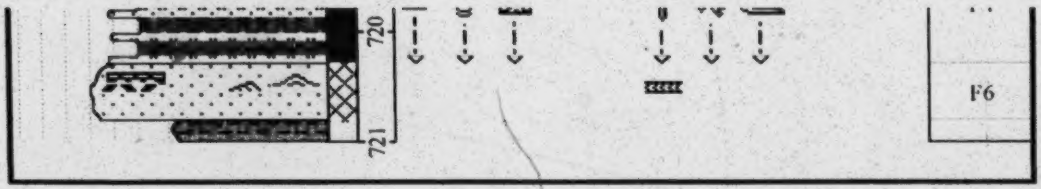
Date Logged: June 11, 2004

Logged by: © 2005 Scott A. Reid

Ground: 822.60 m KB: 826.70 m

Ichnology Research Group




720
721
F6

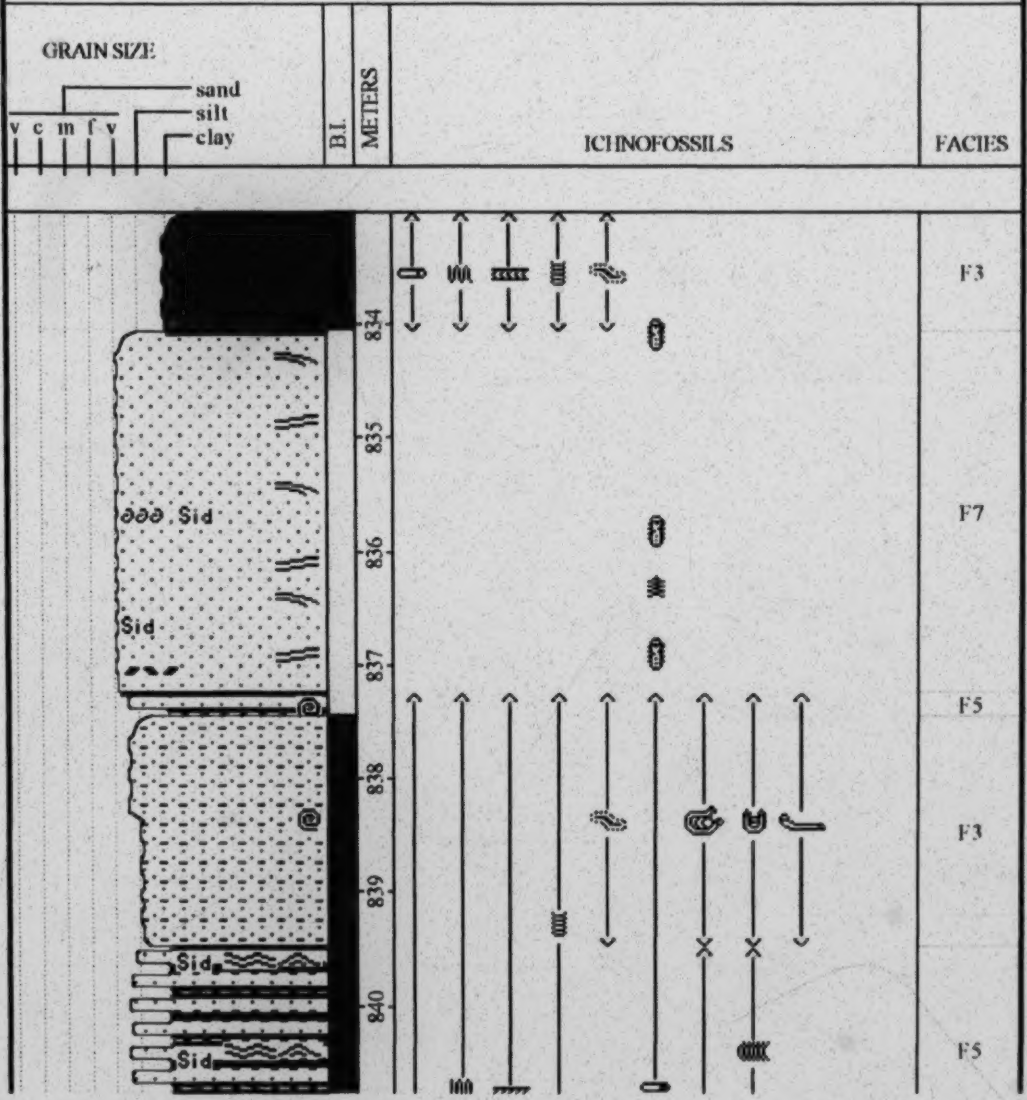
07-25-74-11w6

Date Logged: August 12, 2003

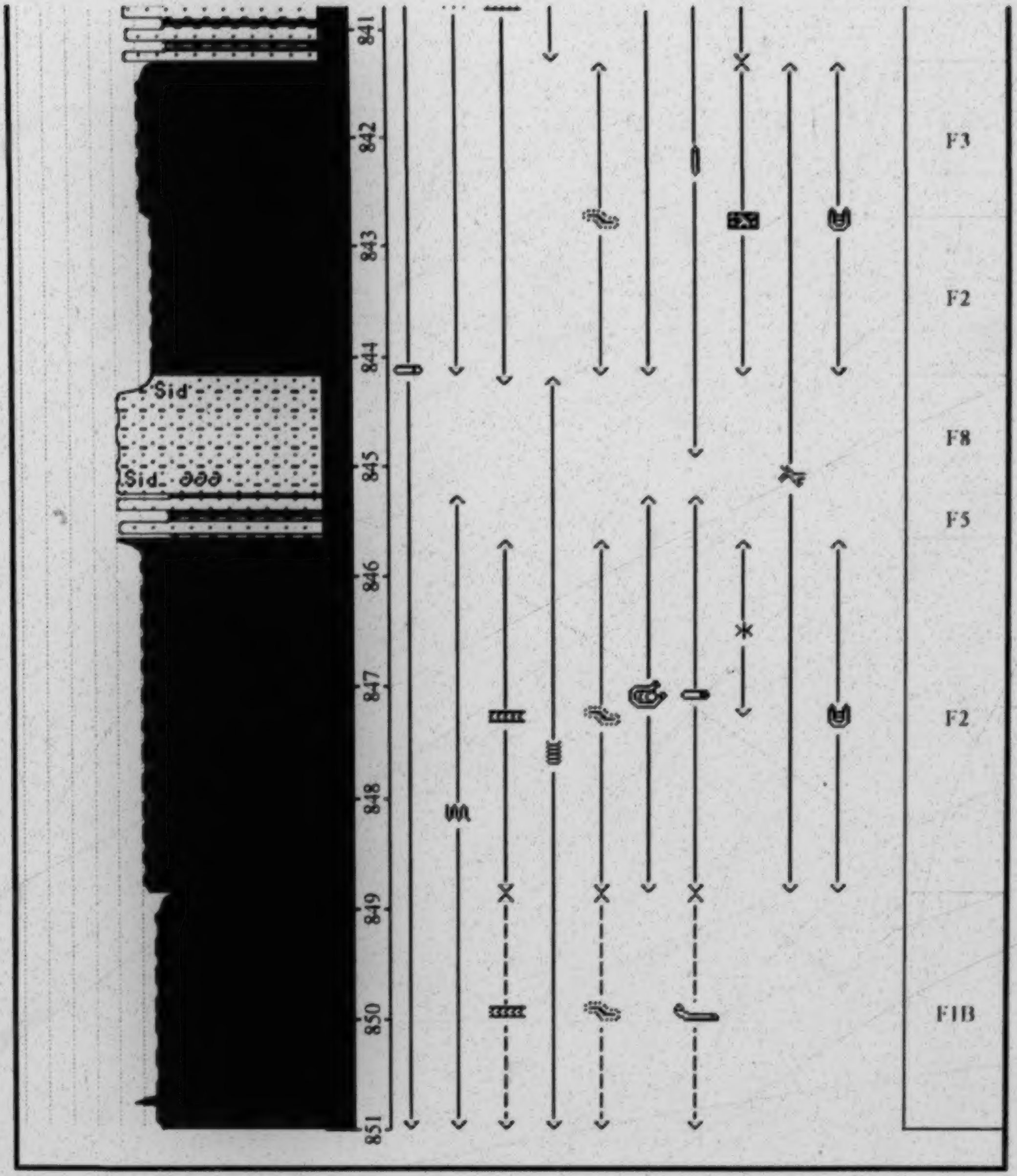
Logged by: © 2005 Scott Reid

Ground: 826.90 m KB: 832.60 m

I.R.G.
Ichnology Research Group



GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
834
835
836
837
838
839
840
∂∂∂, Sid
Sid
Sid
Sid
F3
F7
F5
F3
F5


841
842
843
844
845
846
847
848
849
850
851
Sid
Sid ∂∂∂
F3
F2
F8
F5
F2
F1B

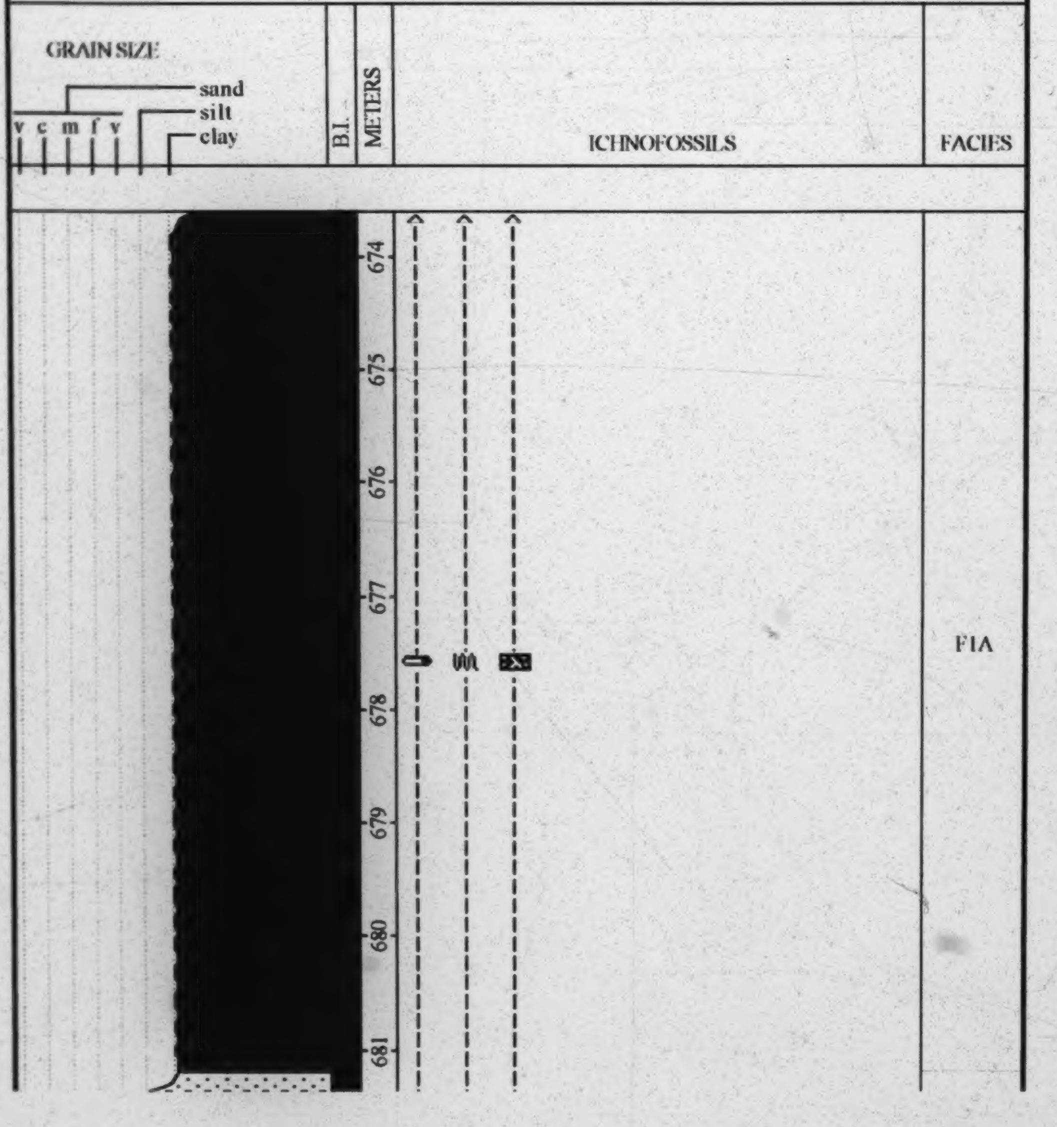
07-25-75-10w6

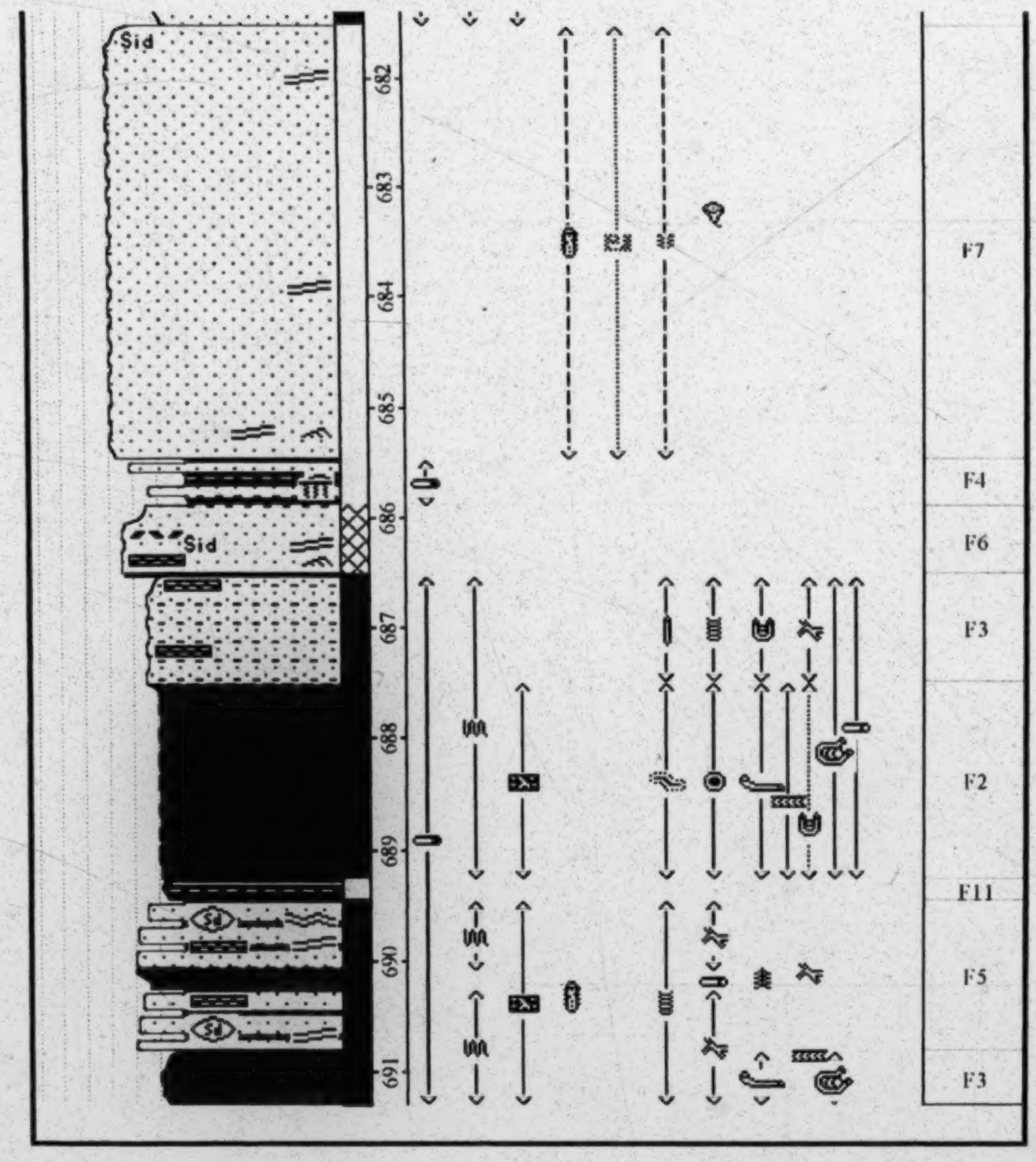
Date Logged: June 20, 2004

Logged by: © 2005 Scott A. Reid

Ground: 822.70 m KB: 826.30 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
674
675
676
677
678
679
680
681
F1A

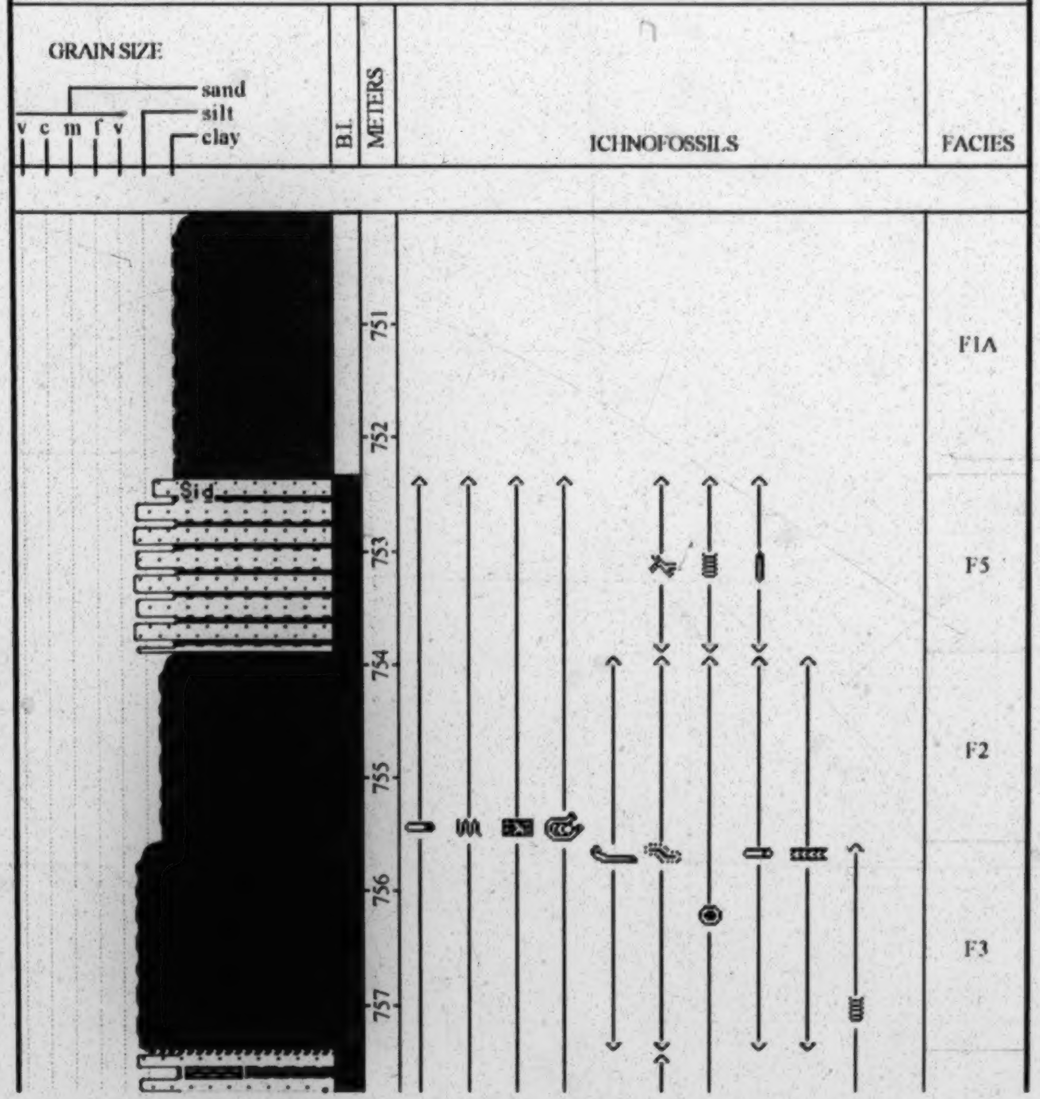

Sid
Sid
Sd
Sd
682
683
684
685
686
687
688
689
690
691
F7
F4
F6
F3
F2
F11
F5
F3

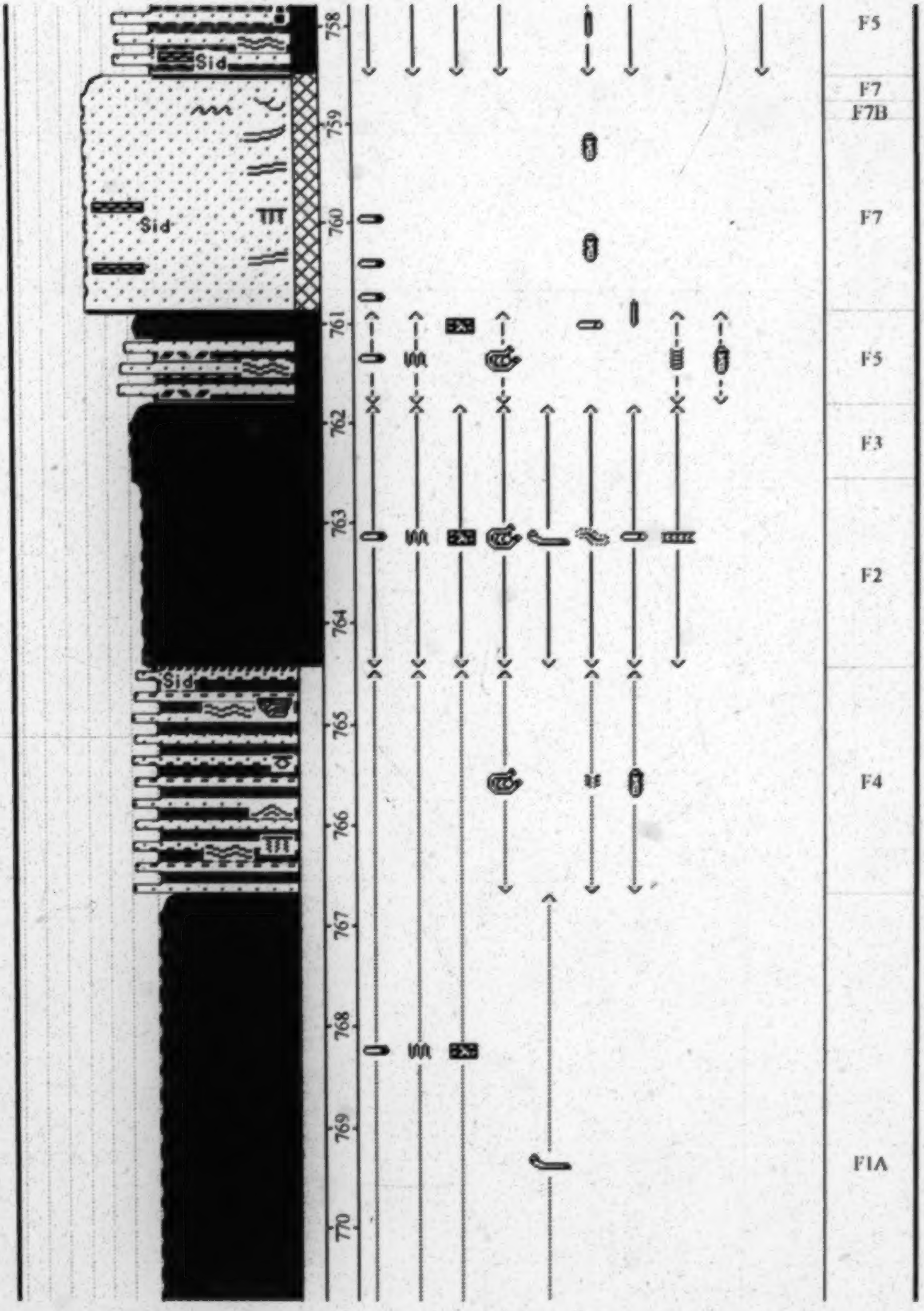
07-26-74-9w6

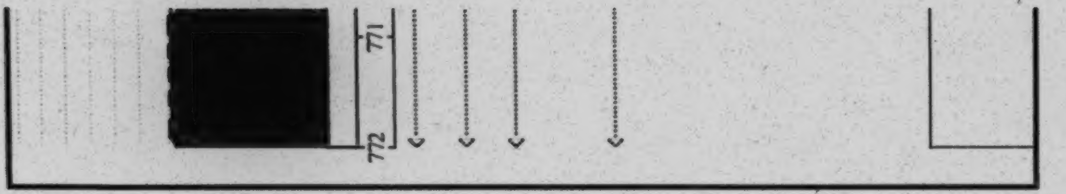
Date Logged: August 13, 2003

Logged by: © 2005 Scott A. Reid

Ground: 787.60 m KB: 793.10 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
Sid
751
752
753
754
755
756
757
F1A
F5
F2
F3


758
759
760
761
762
763
764
765
766
767
768
769
770
Sid
Sid
Sid
F5
F7
F7B
F7
F5
F3
F2
F4
F1A

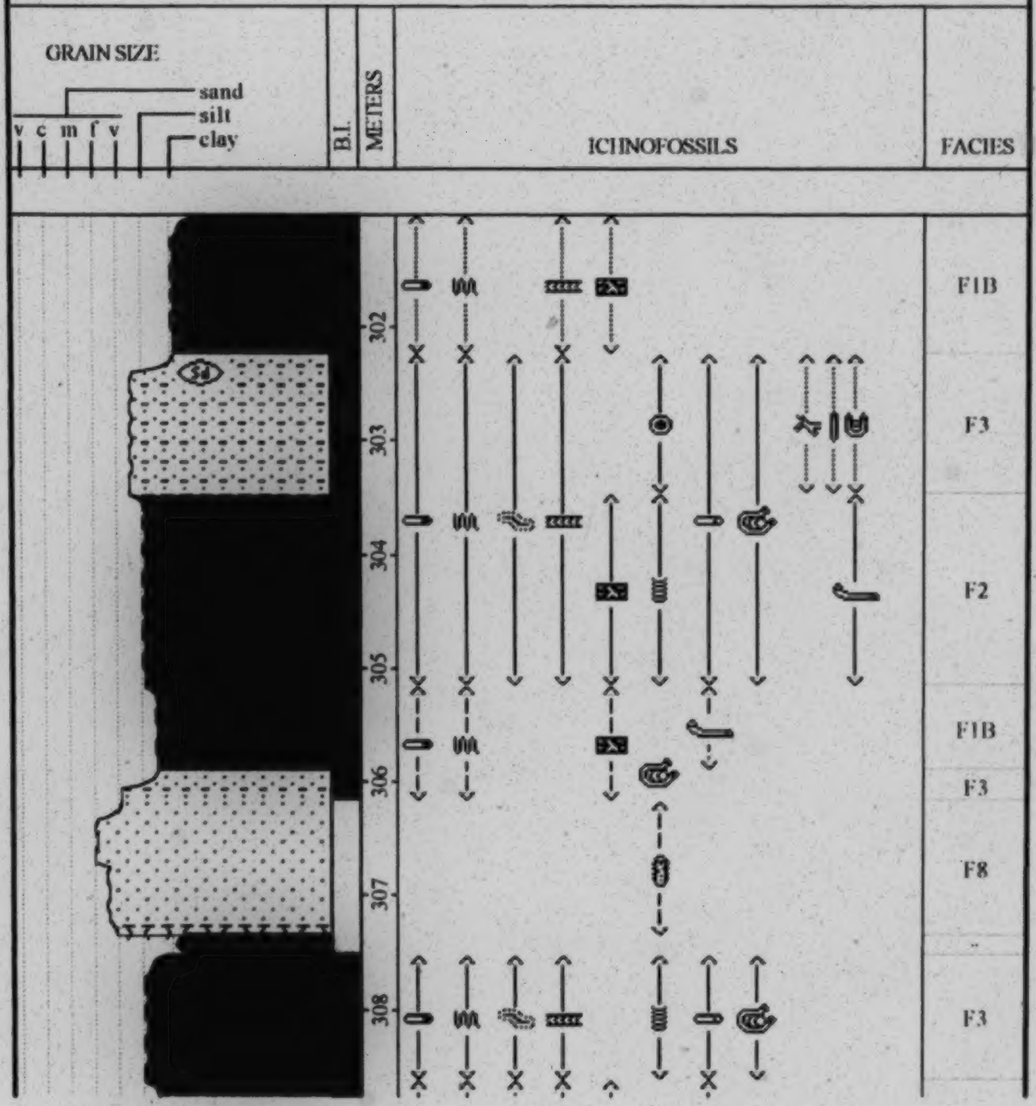

771
772

08-01-79-9w6

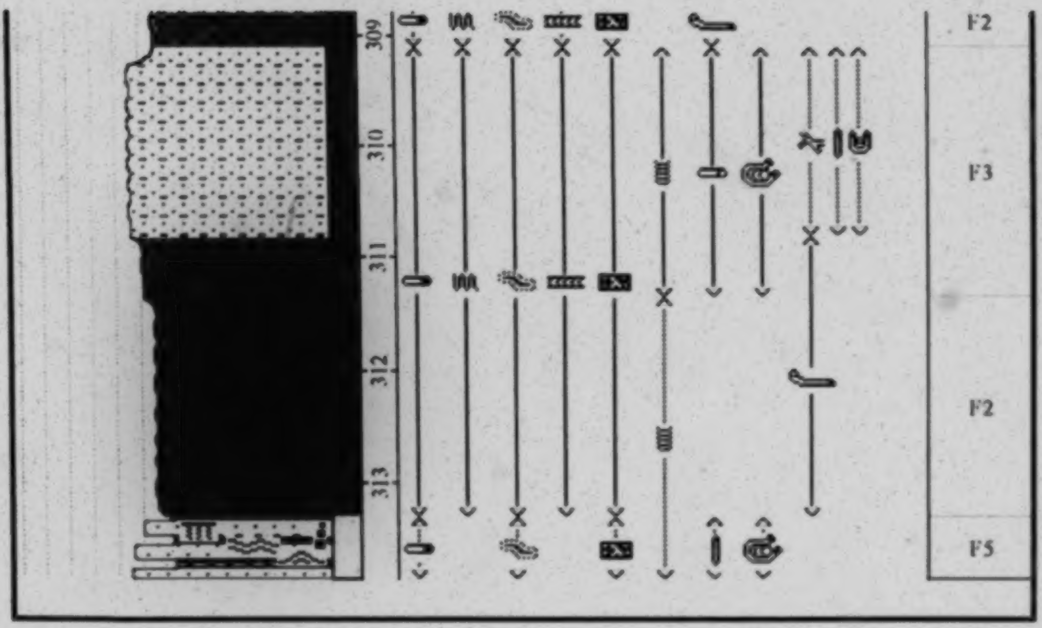
Date Logged: December 9, 2004

Logged by: © 2005 Scott A. Reid

Ground: 716.90 m KB: 719.70 m



GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
302
303
304
305
306
307
308
Sd
F1B
F3
F2
F1B
F3
F8
F3


309
310
311
312
313
F2
F3
F2
F5

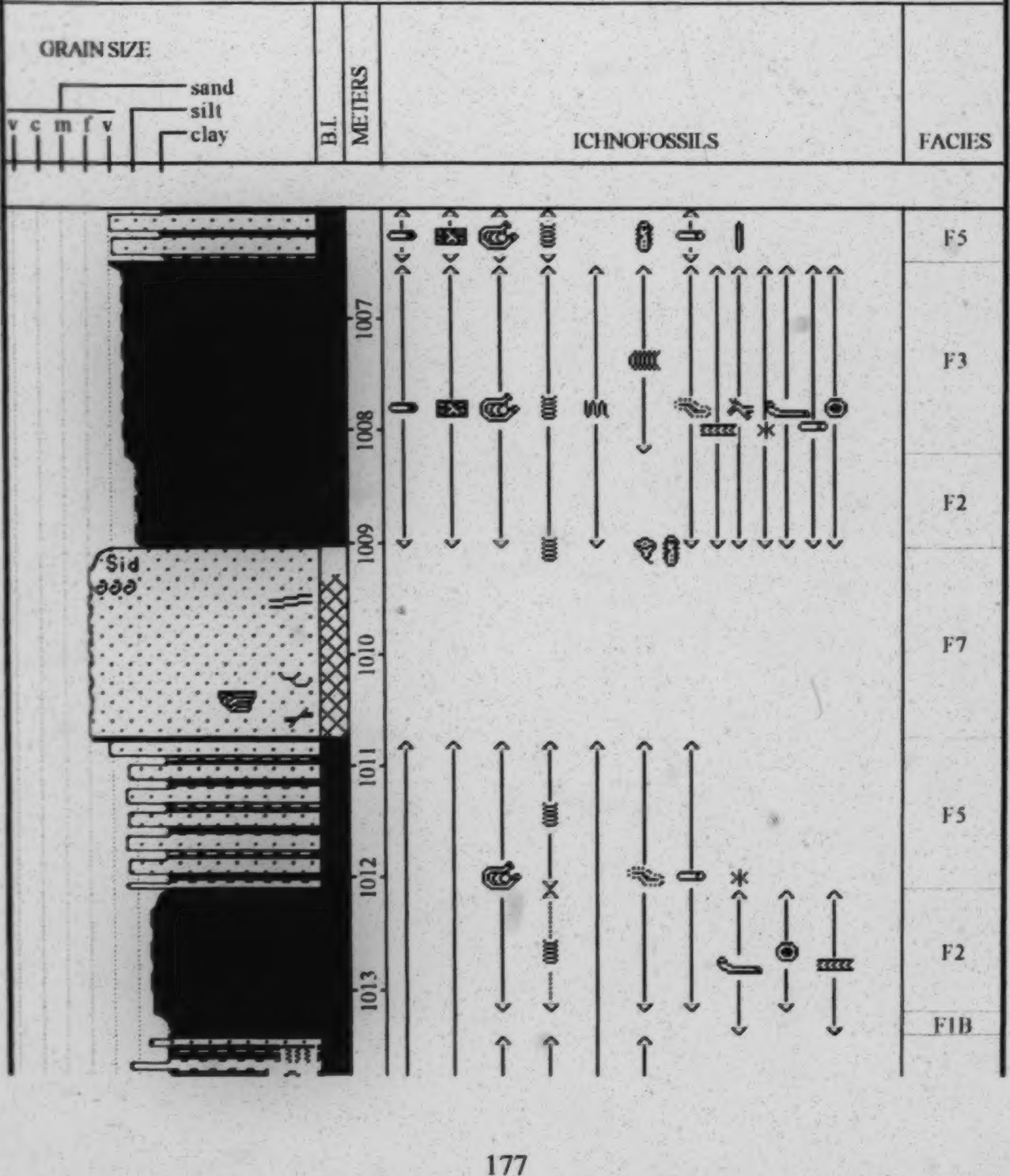
08-09-73-12w6

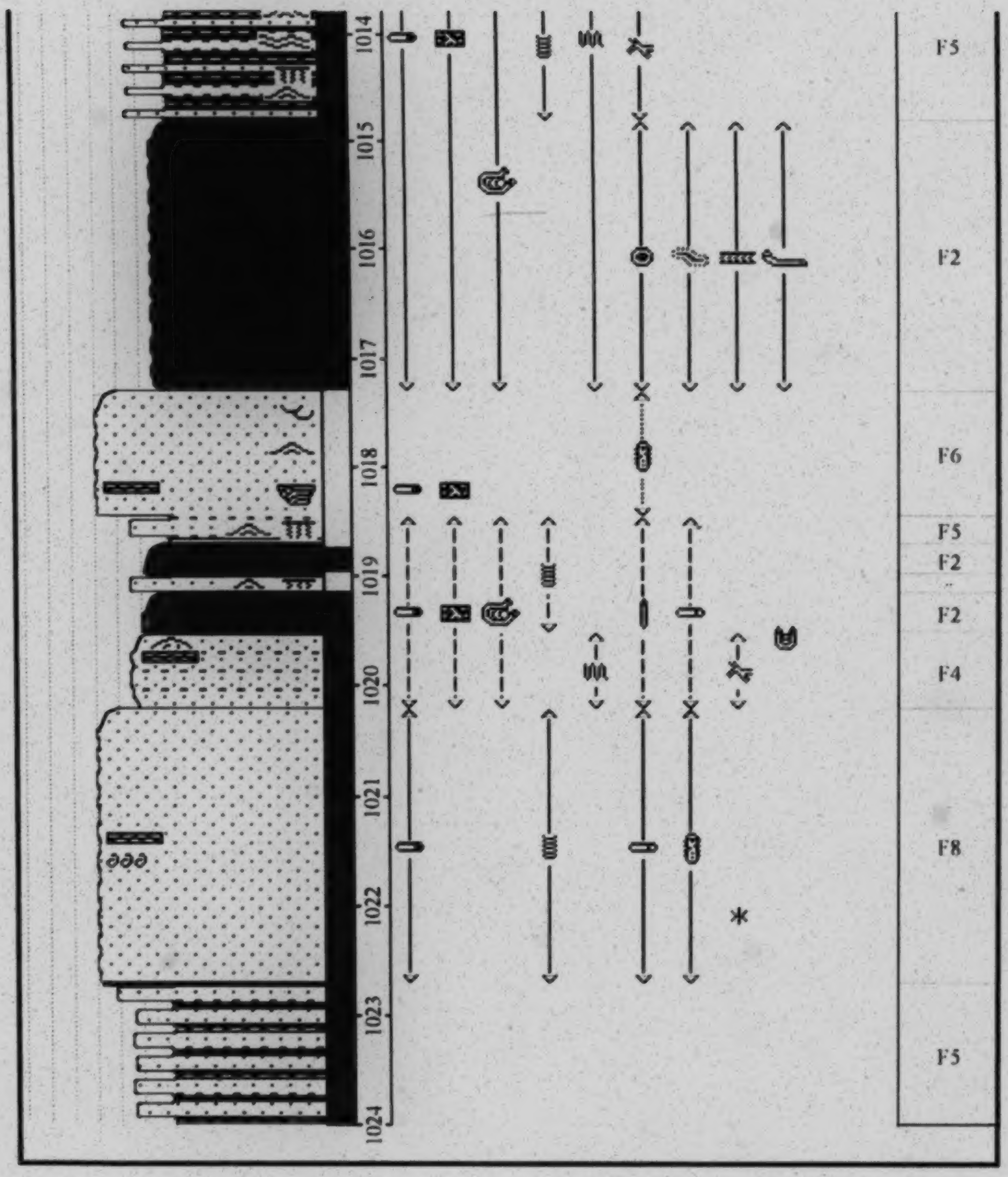
Date Logged: June 11, 2004

Logged by: © 2005 Scott A. Reid

Ground: 788.50 m KB: 794.00 m

I.R.G.
Ichnology Research Group




1014
1015
1016
1017
1018
1019
1020
1021
1022
1023
1024
F5
F2
F6
F5
F2
F2
F4
F8
F5

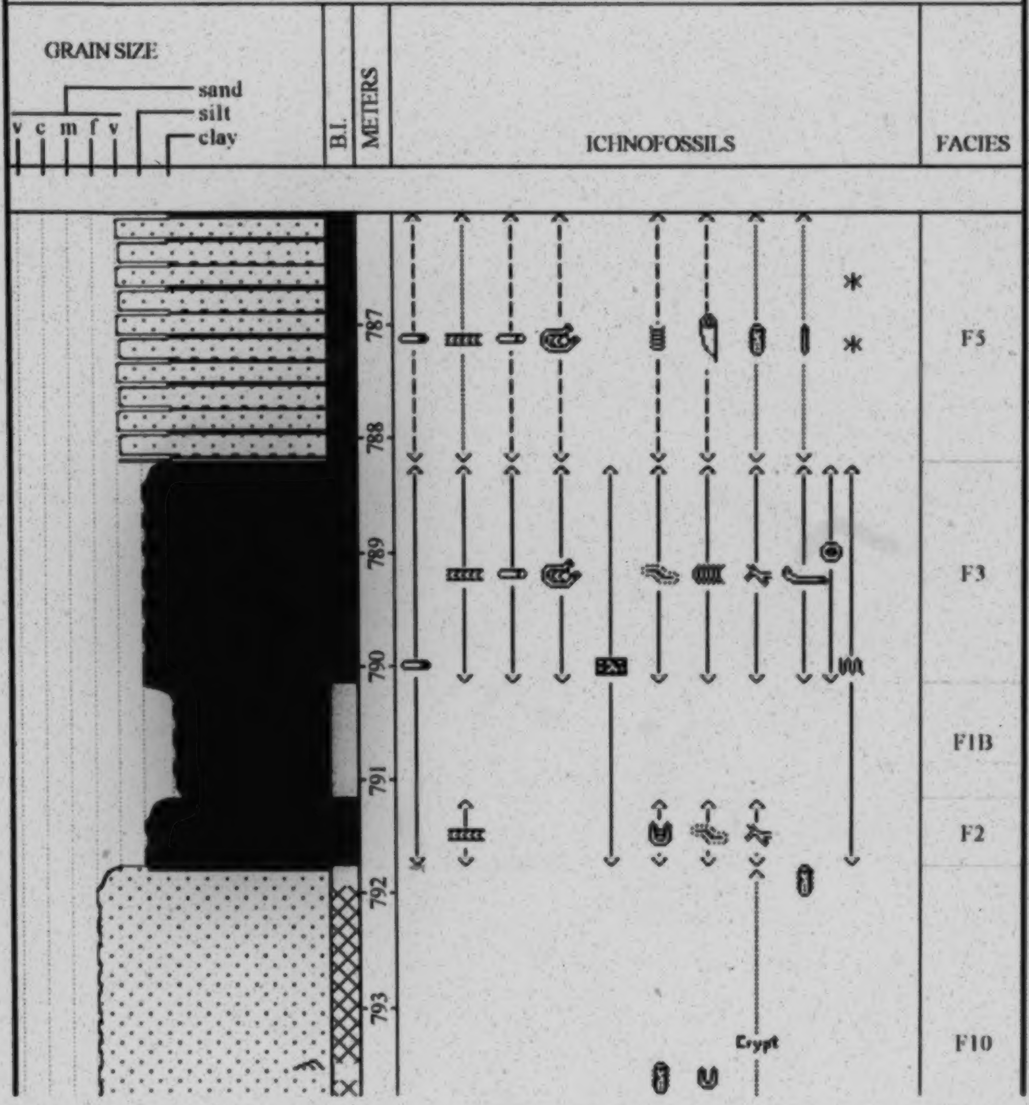
08-10-75-12w6

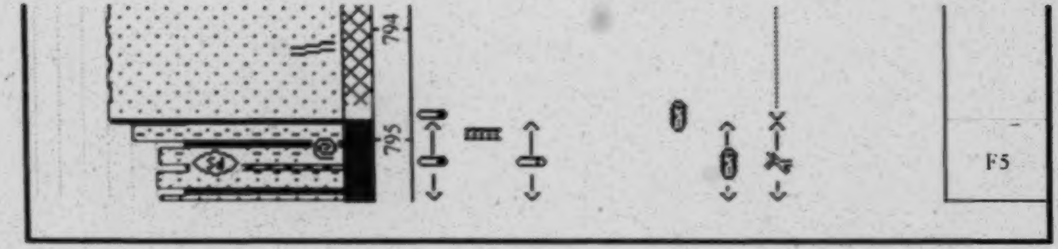
Date Logged: July 28, 2003

Logged by: © 2005 Scott A. Reid

Ground: 834.30 m KB: 839.00 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
787
788
789
790
791
792
793
F5
F3
F1B
F2
F10
Crypt

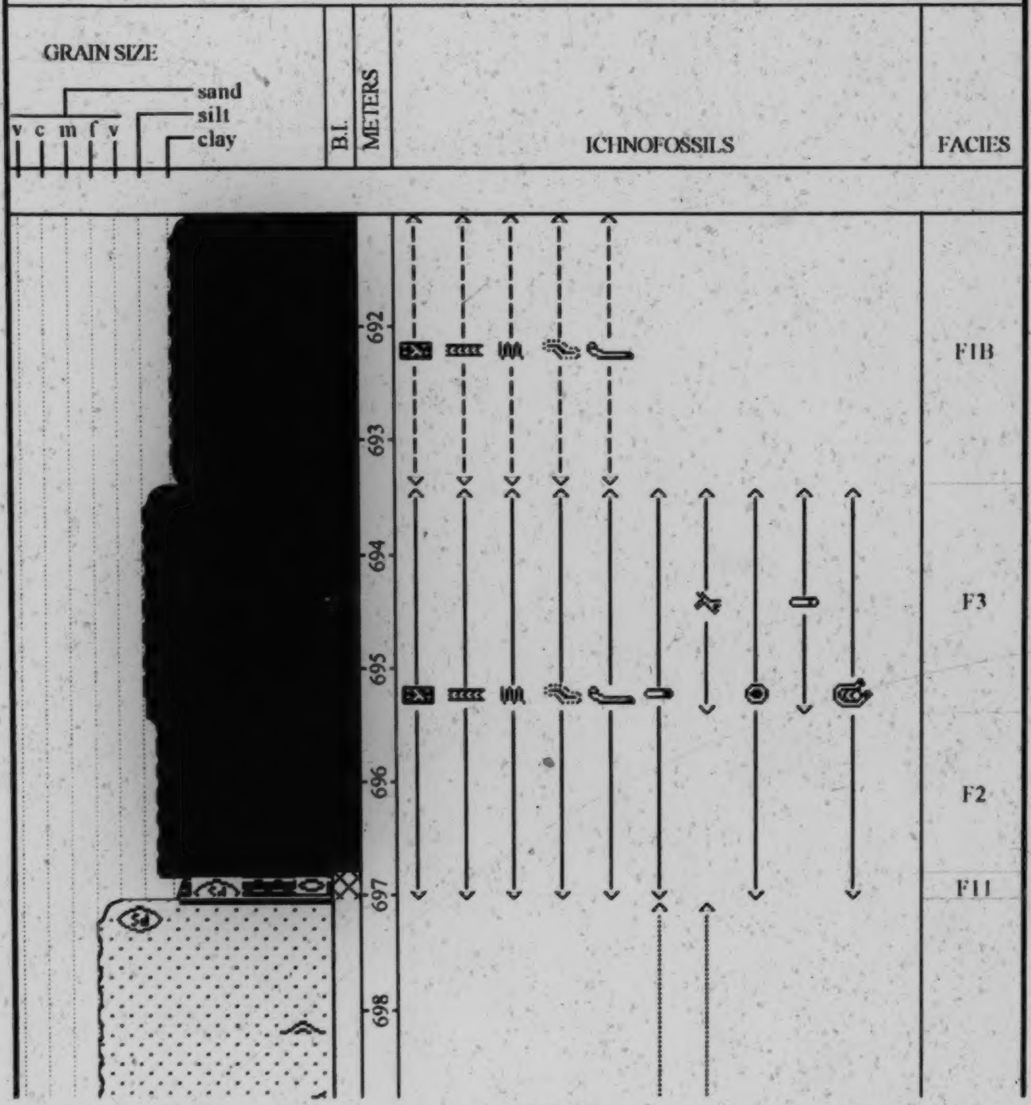

794
795
F5

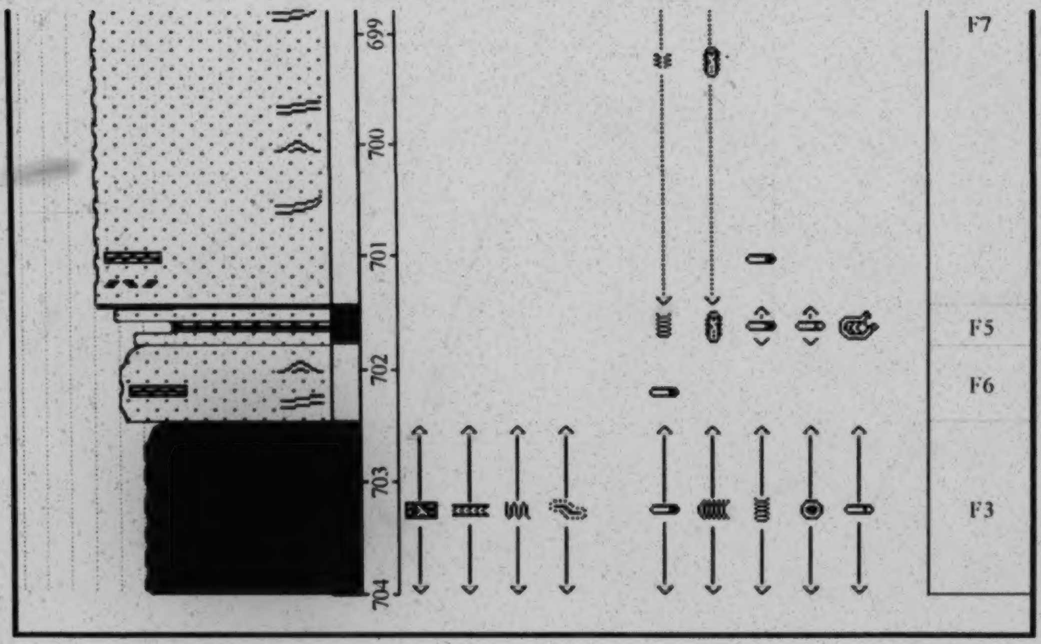
08-16-75-8w6

Date Logged: June 13, 2003

Logged by: © 2005 Scott A. Reid

Ground: 823.40 m KB: 826.40 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
692
693
694
695
696
697
698
F1B
F3
F2
F11


F7
F5
F6
F3

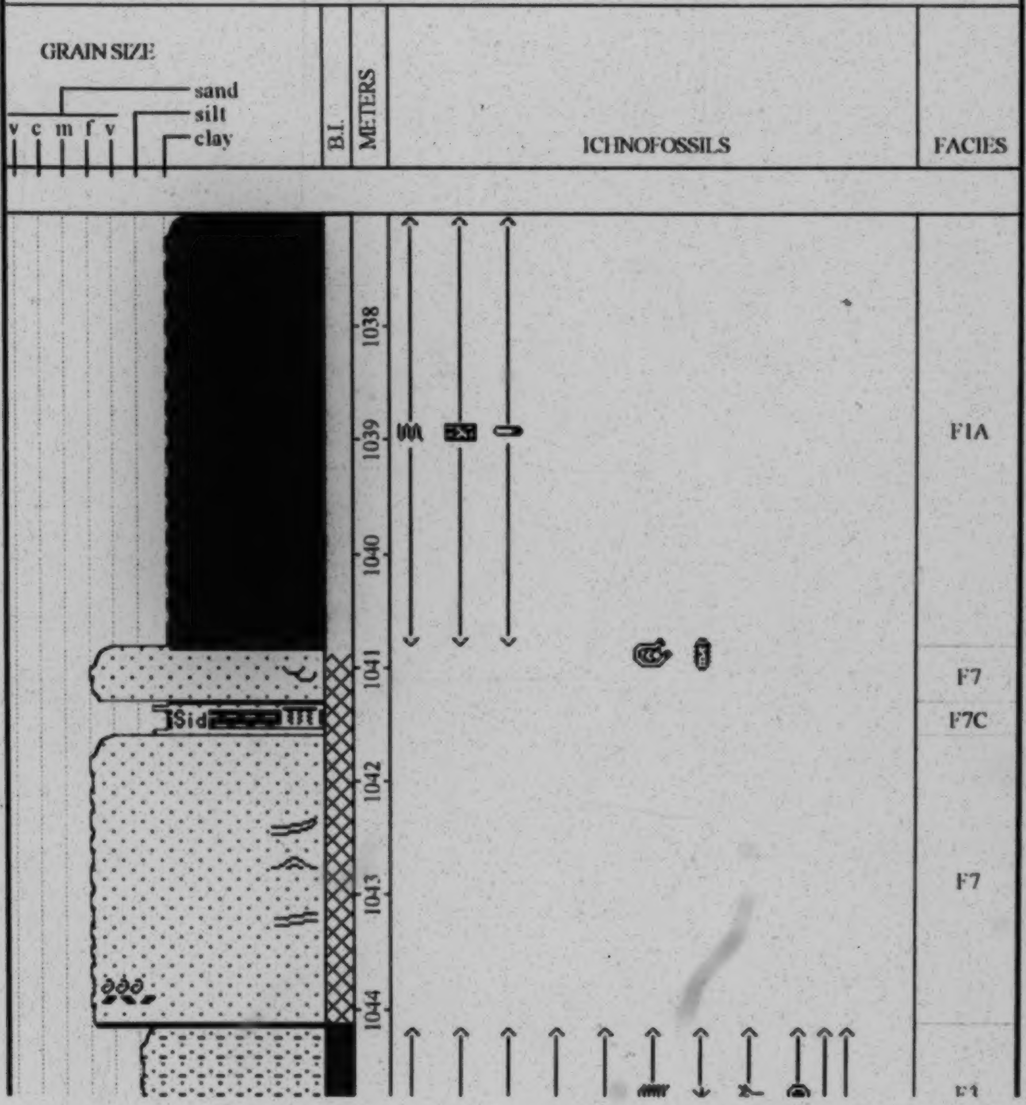
08-23-71-8w6

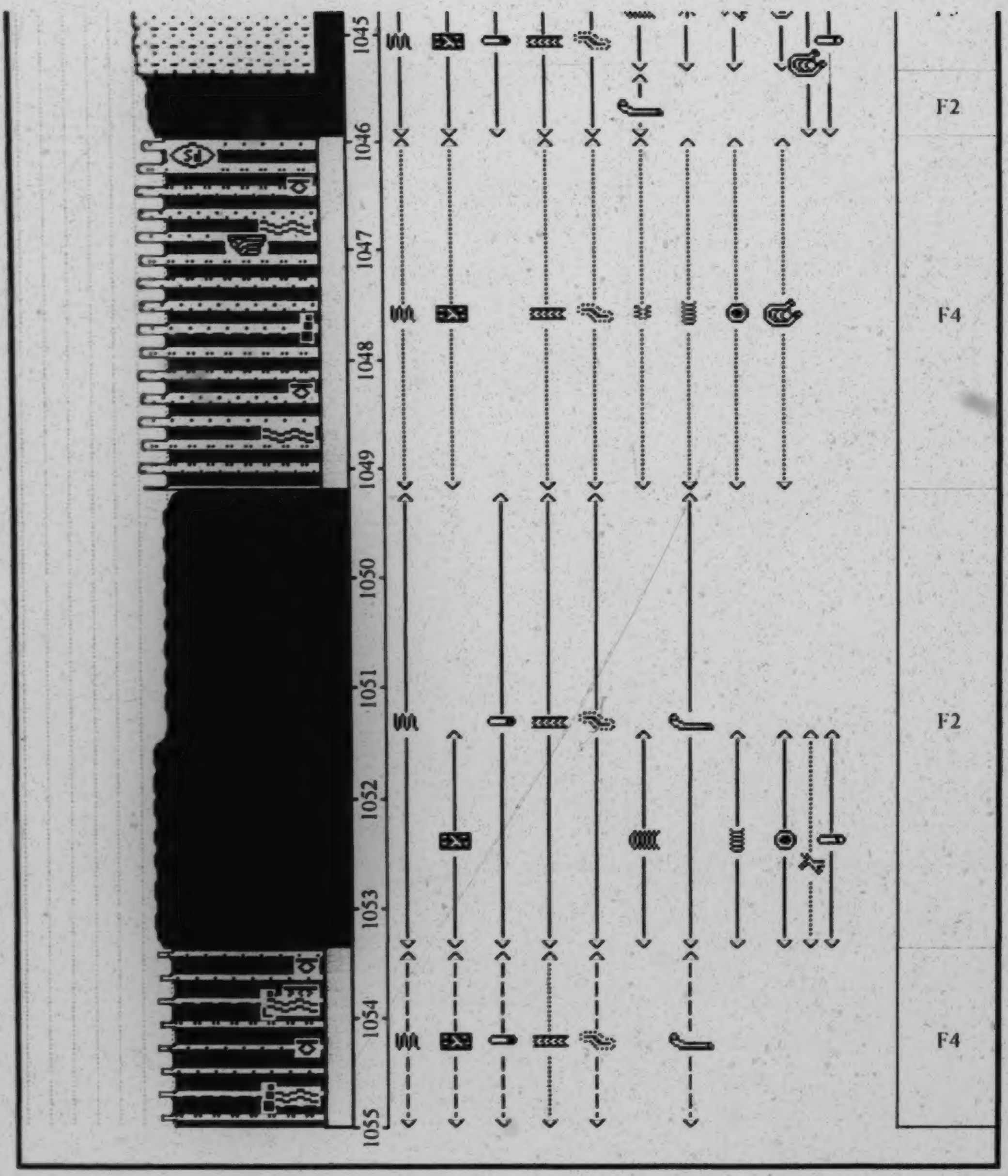
Date Logged: June 8, 2004

Logged by: © 2005 Scott A. Reid

Ground: 719.40 m KB: 723.50 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
1038
1039
1040
1041
1042
1043
1044
Sid
F1A
F7
F7C
F7
F1



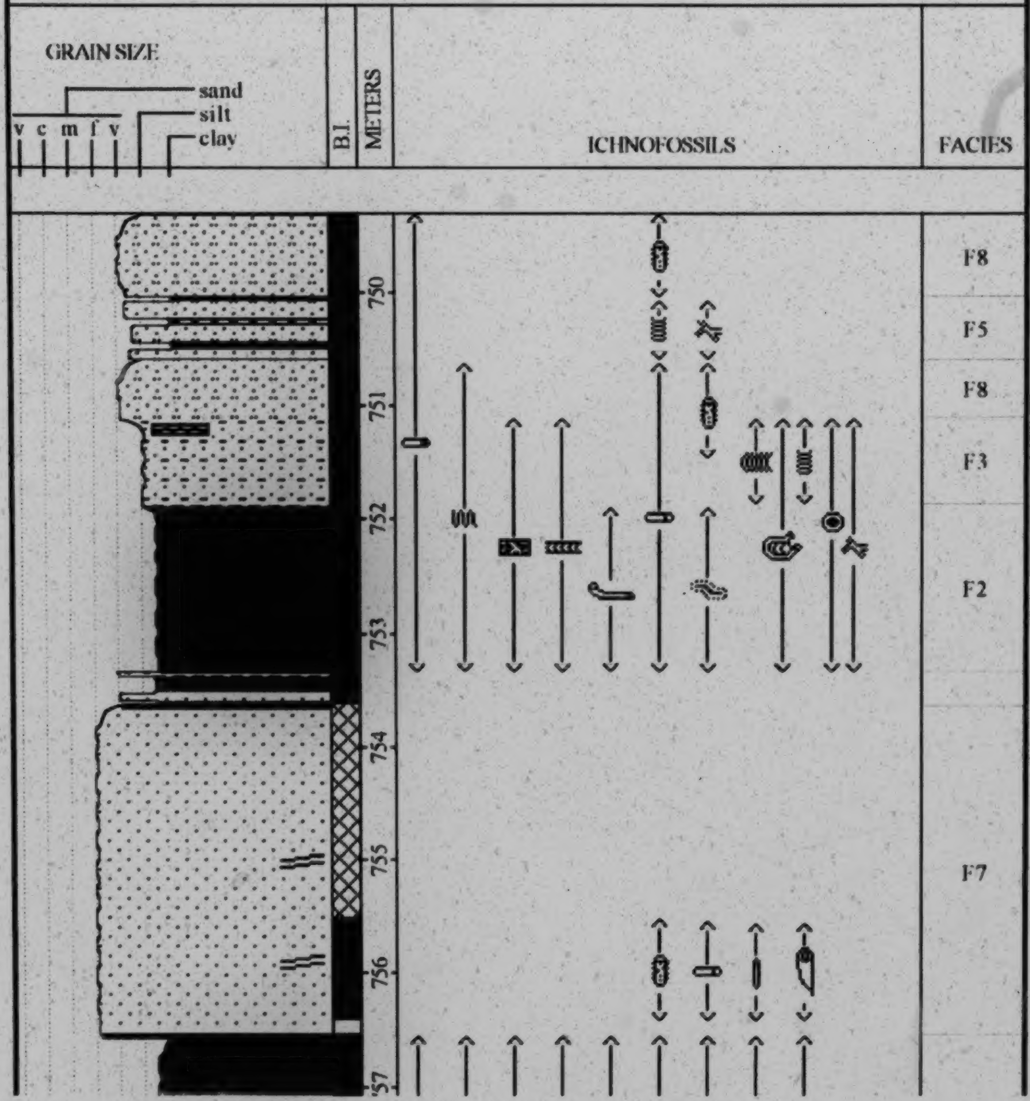
F2
F4
F2
F4

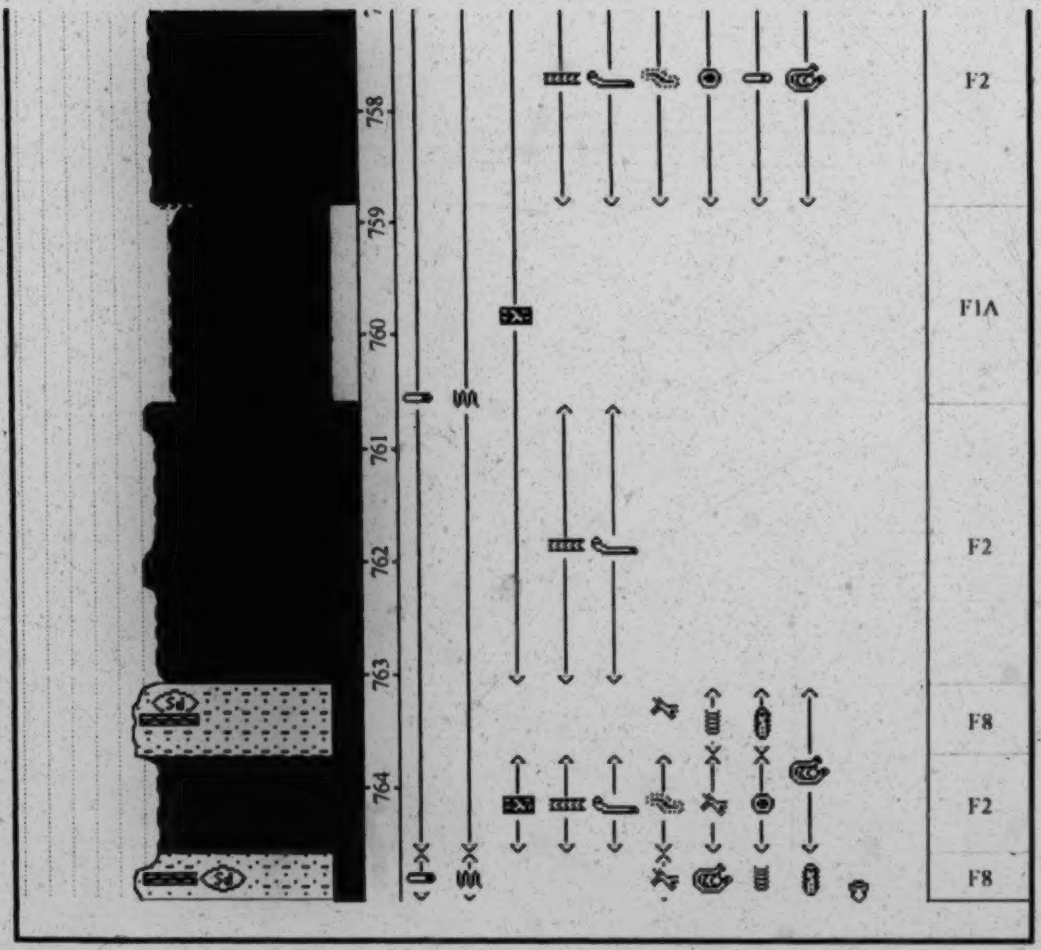
08-26-75-11w6

Date Logged: June 22, 2004

Logged by: © 2005 Scott A. Reid

Ground: 862.30 m KB: 866.90 m


GRAIN SIZE
sand
silt
clay
v
c
m
f
v
B.I.
METERS
ICHNOFOSSILS
FACIES
750
751
752
753
754
755
756
757
F8
F5
F8
F3
F2
F7


758
759
760
761
762
763
764
Sd
Sd
F2
F1A
F2
F8
F2
F8

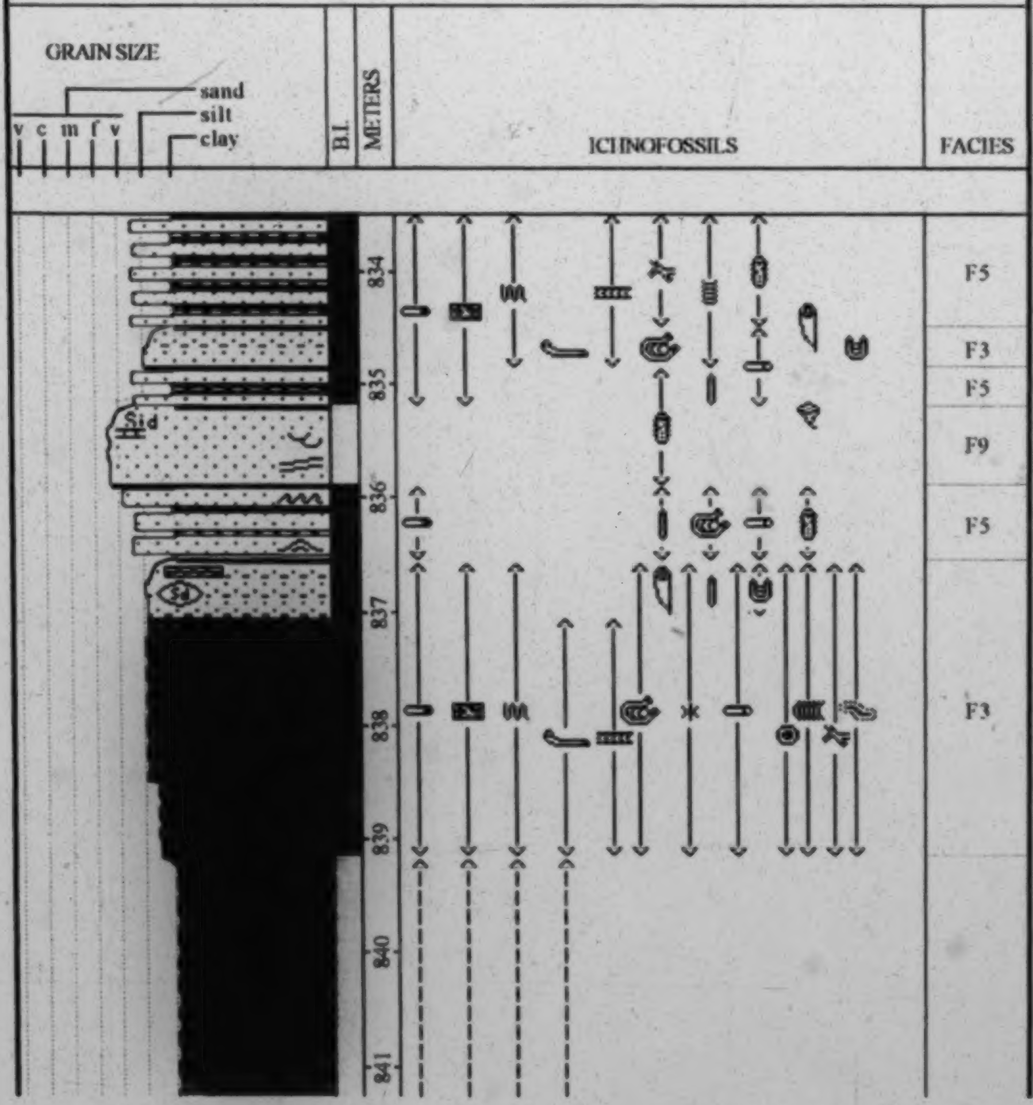
08-30-75-11w6

Date Logged: July 11, 2003

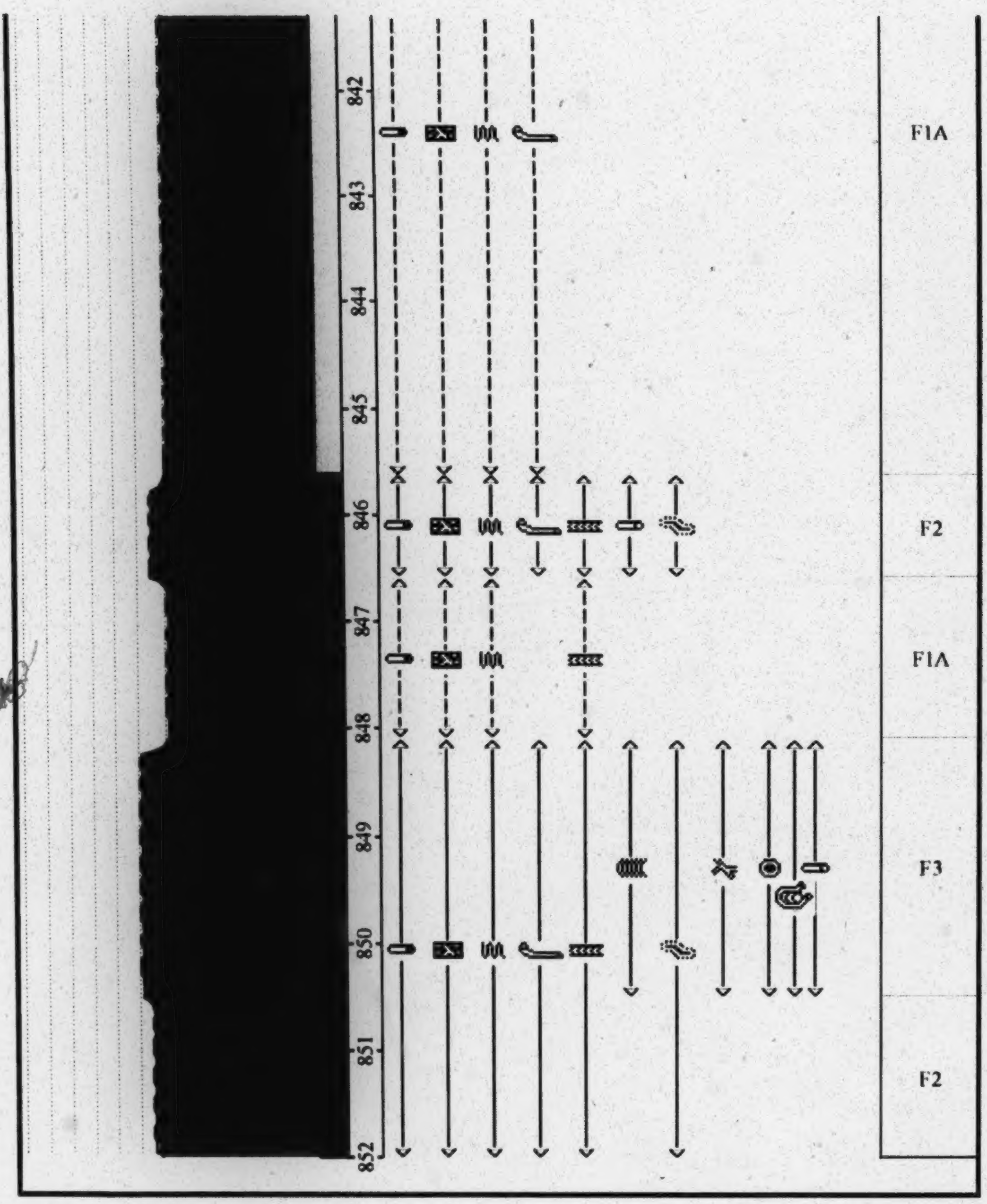
Logged by: © 2005 Scott A. Reid

Ground: 938.00 m KB: 942.60 m

I.R.G.
Ichnology Research Group



GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
Sid
Sd
834
835
836
837
838
839
840
841
F5
F3
F5
F9
F5
F3


842
843
844
845
846
847
848
849
850
851
852
F1A
F2
F1A
F3
F2

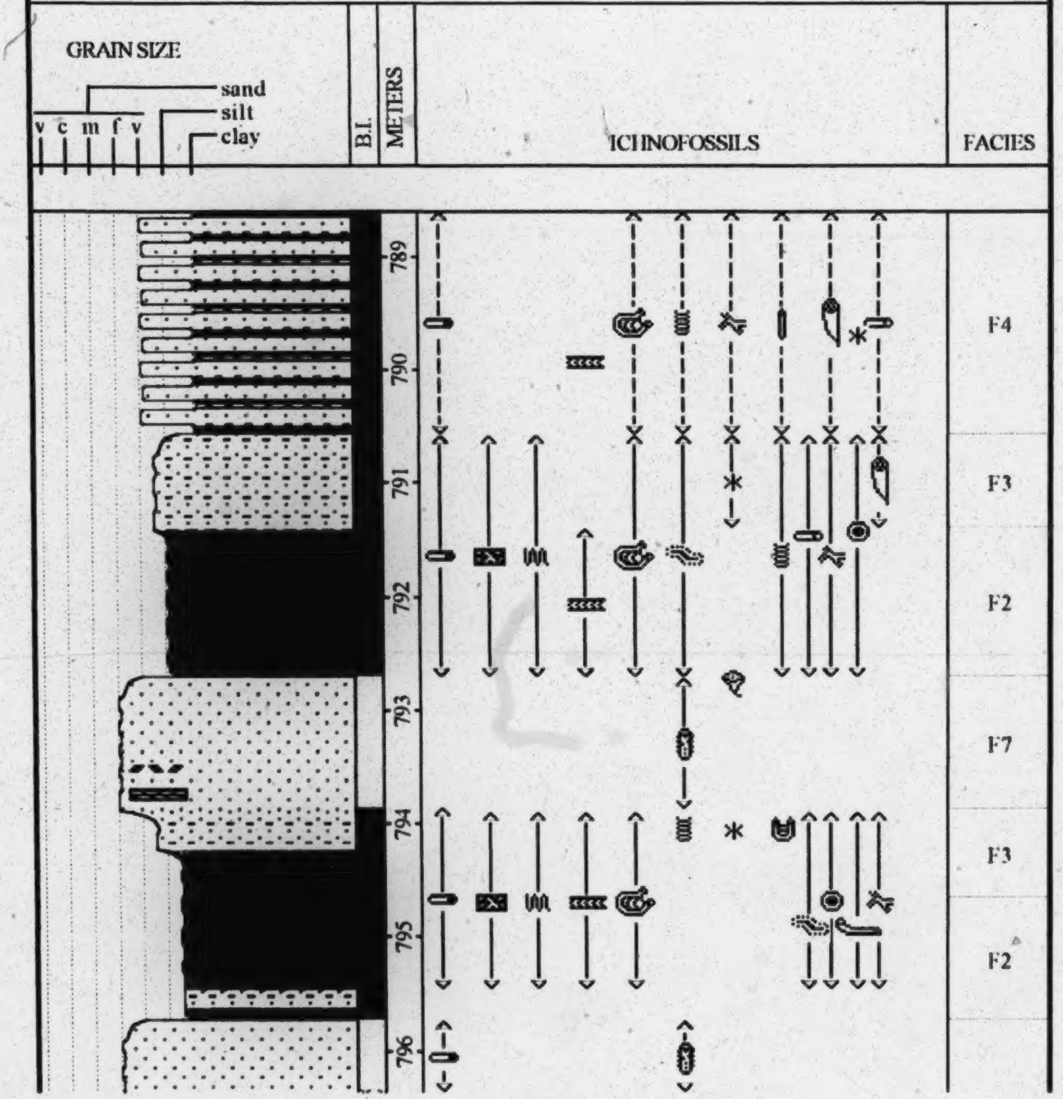
08-34-74-12w6

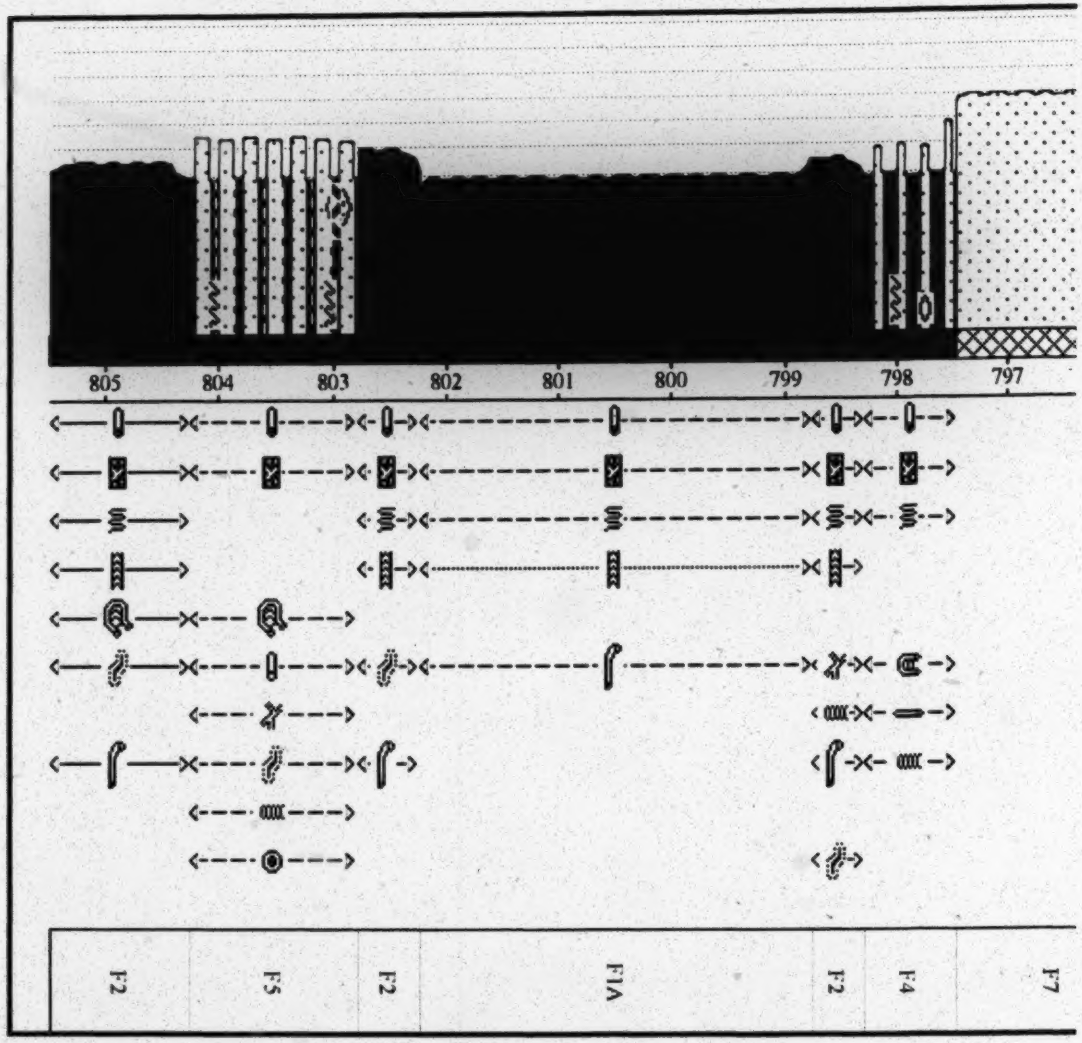
Date Logged: July 29, 2003

Logged by: © 2005 Scott A. Reid

Ground: 800.10 m KB: 803.10 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
789
790
791
792
793
794
795
796
F4
F3
F2
F7
F3
F2

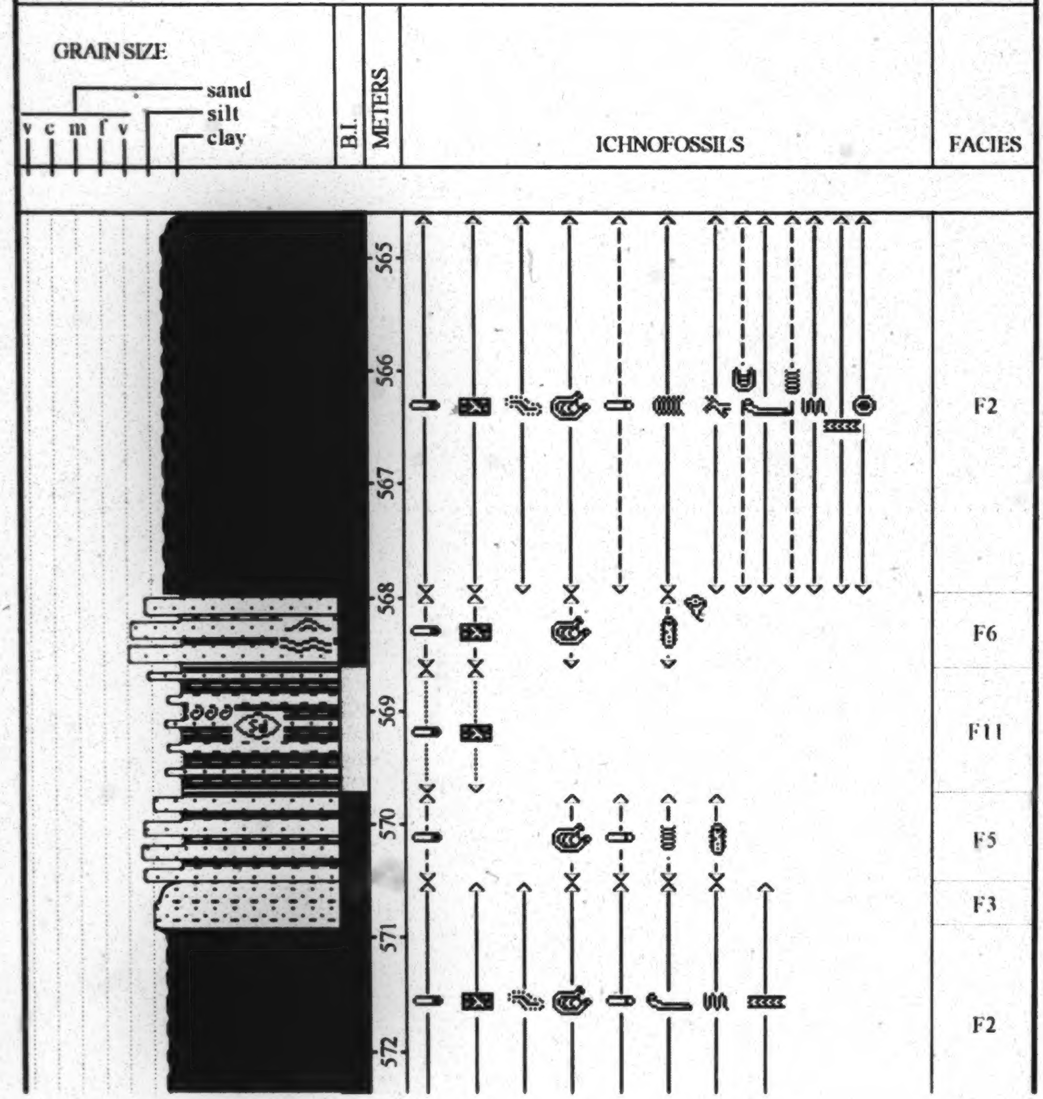

805
804
803
802
801
800
799
798
797
F2
F5
F2
F1A
F2
F4
F7

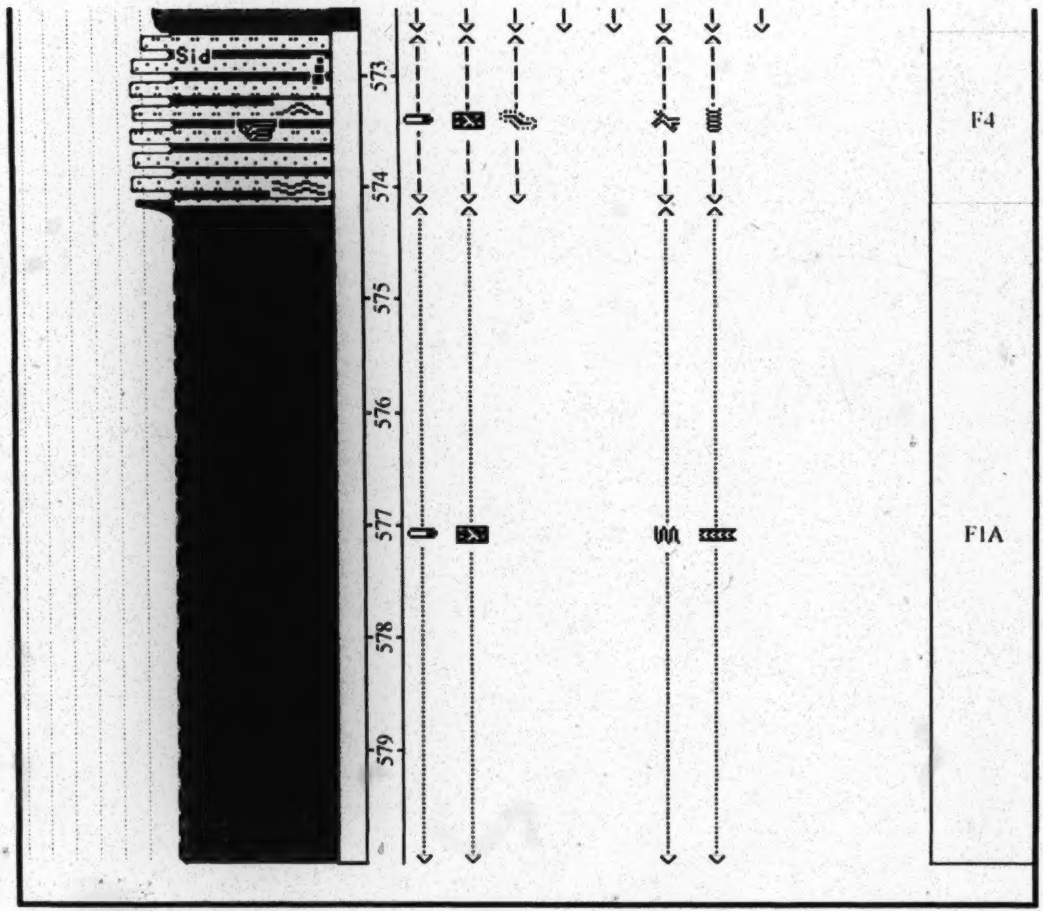
08-35-76-8w6

Date Logged: June 22, 2004

Logged by: © 2005 Scott A. Reid

Ground: 806.40 m KB: 810.00 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
565
566
567
568
569
570
571
572
F2
F6
F11
F5
F3
F2

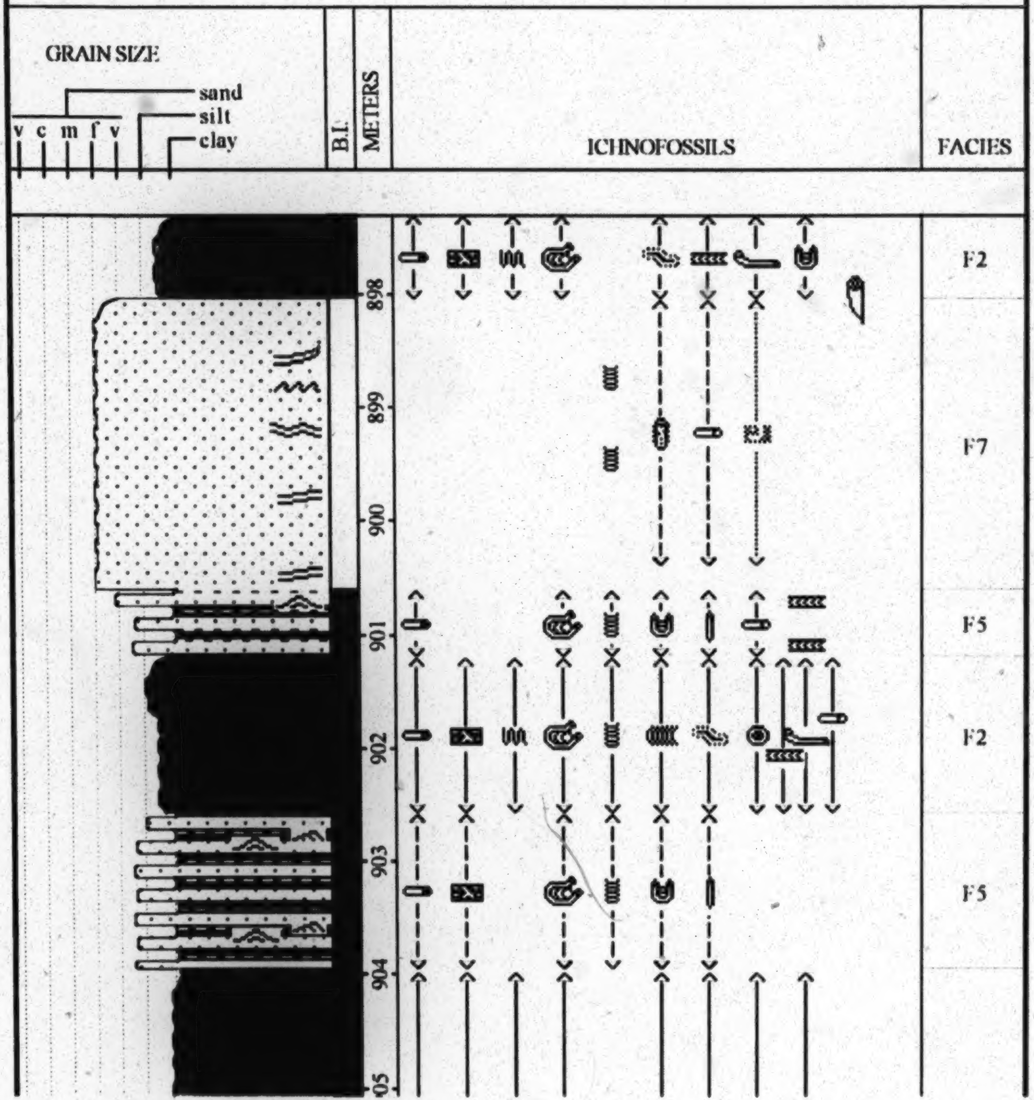

Sid
F4
F1A

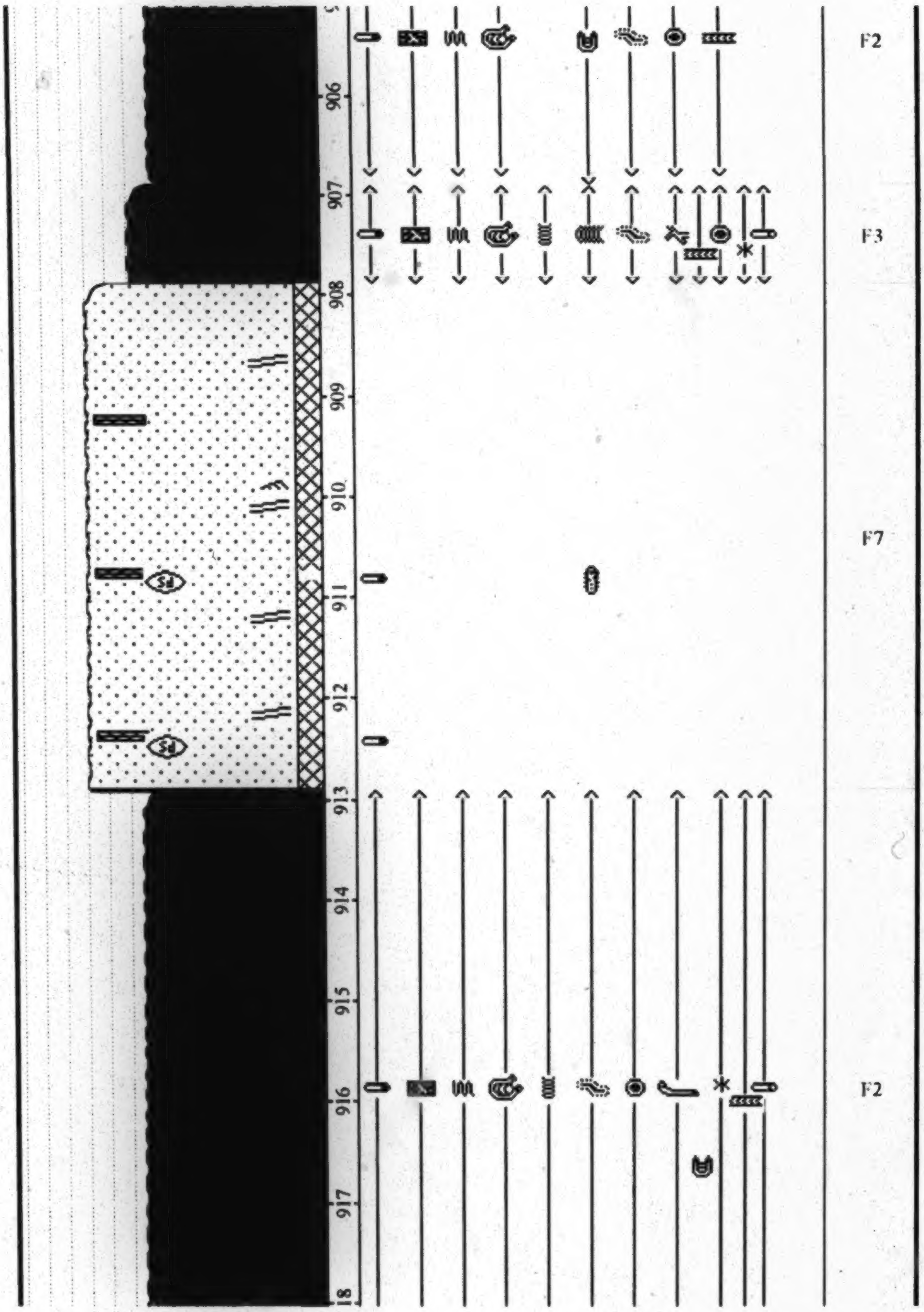
10-01-74-11w6

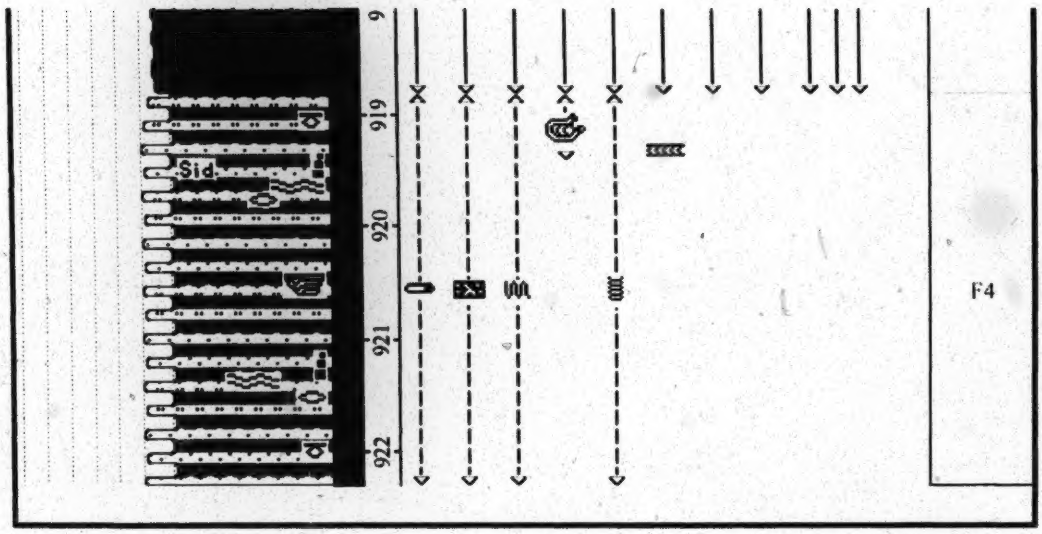
Date Logged: August 6, 2003

Logged by: © 2005 Scott A. Reid

Ground: 795.20 m KB: 798.90 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
898
899
900
901
902
903
904
05
F2
F7
F5
F2
F5


PS
PS
F2
F3
F7
F2

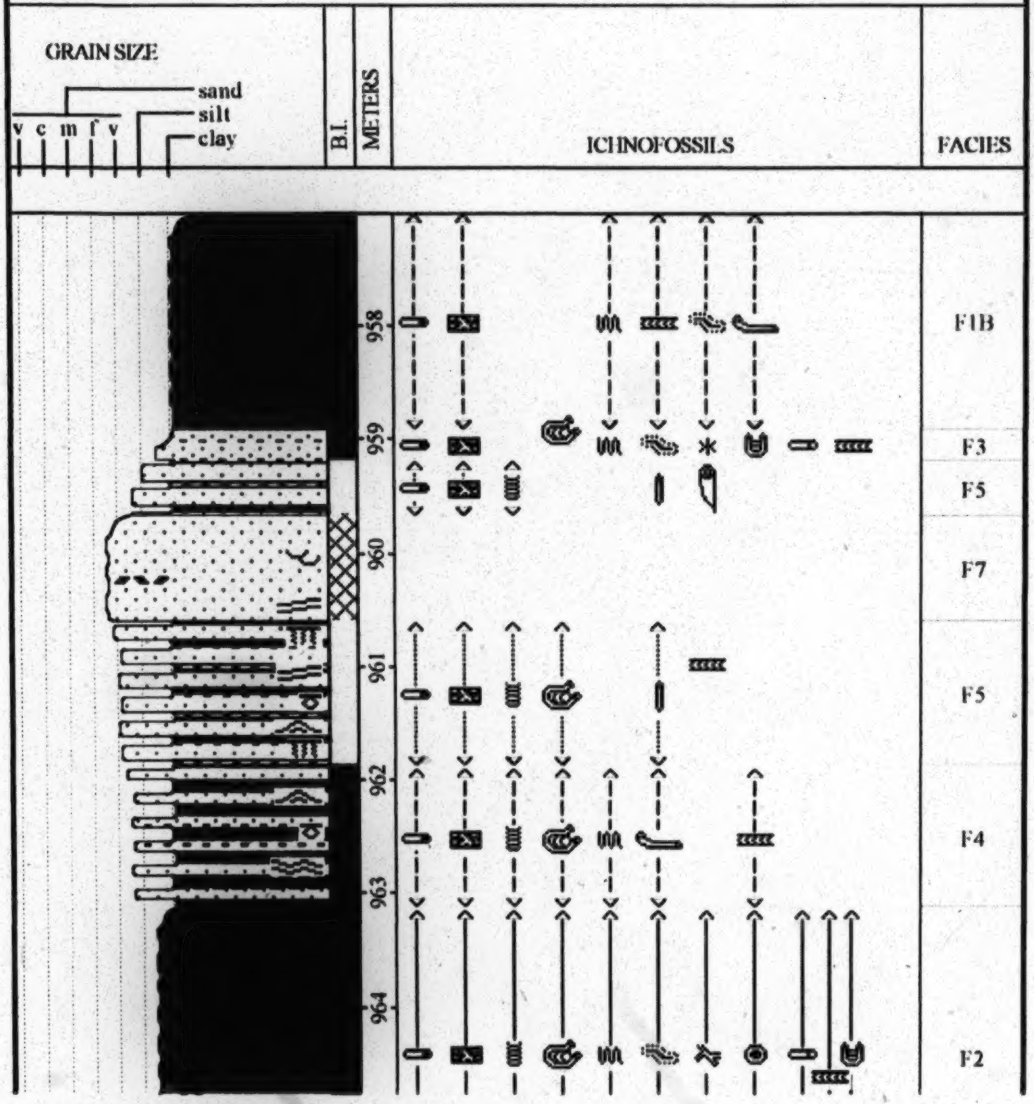

Sid
F4

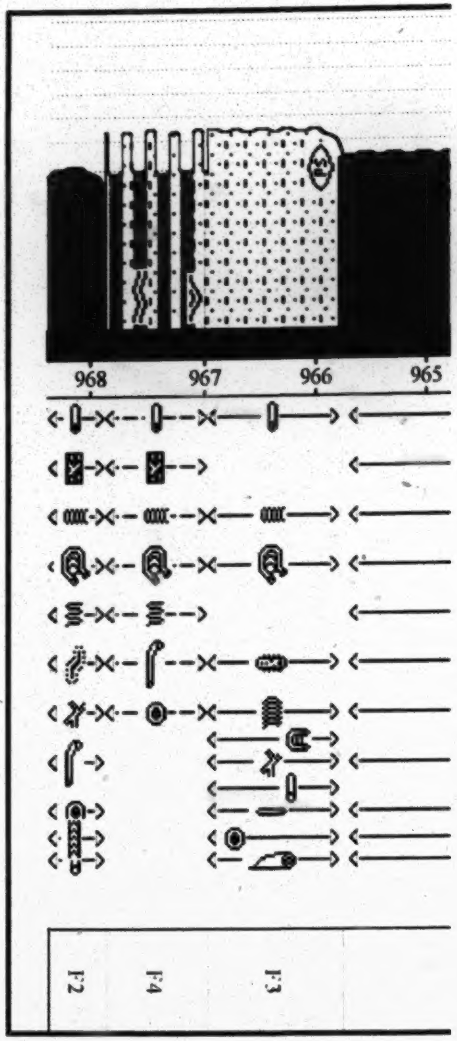
10-02-73-10w6

Date Logged: August 5, 2003

Logged by: © 2005 Scott A. Reid

Ground: 749.20 m KB: 759.70 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
958
959
960
961
962
963
964
F1B
F3
F5
F7
F5
F4
F2

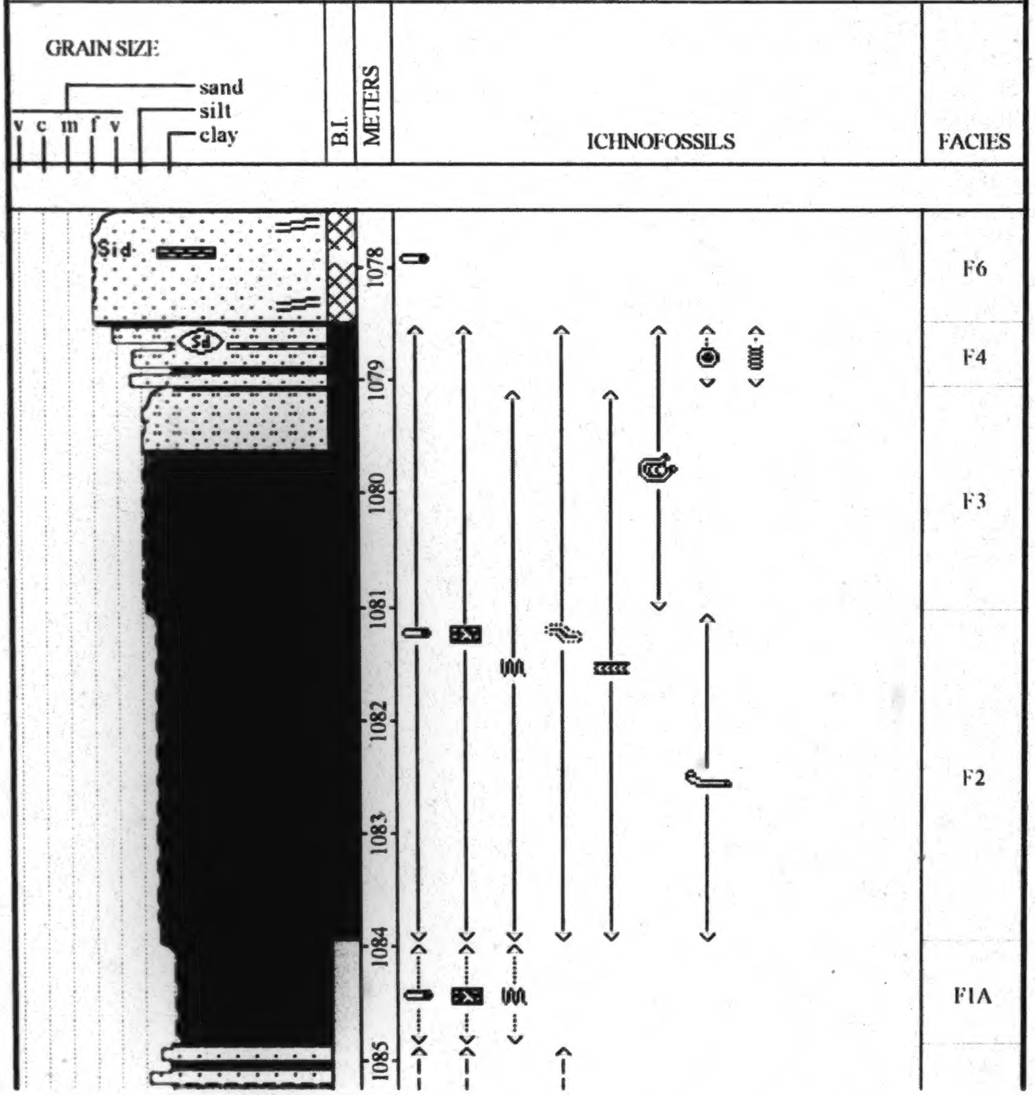

968
967
966
965
F2
F4
F3

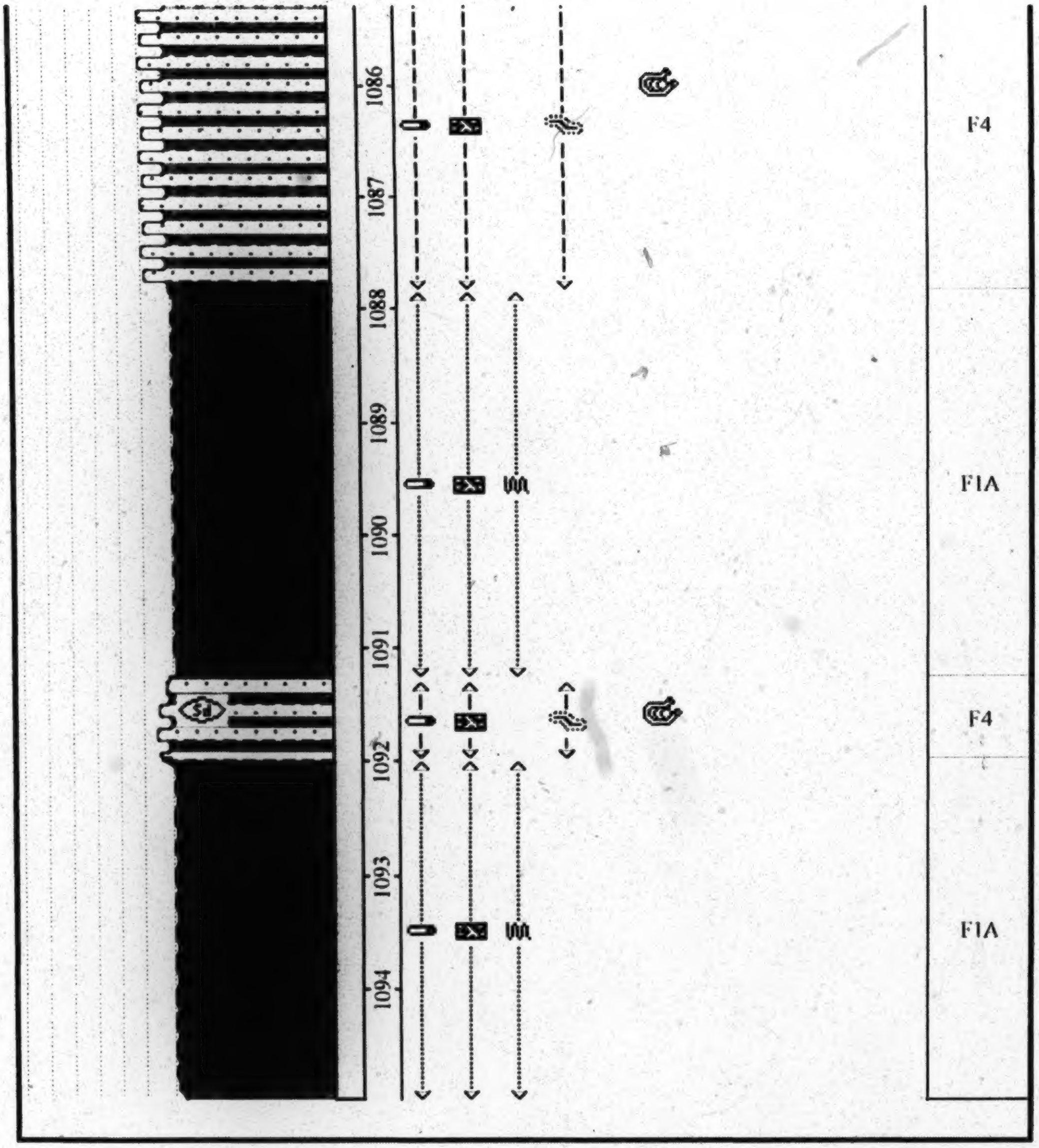
10-23-72-11w6

Date Logged: June 10, 2004

Logged by: © 2005 Scott A. Reid

Ground: 777.20 m KB: 782.40 m



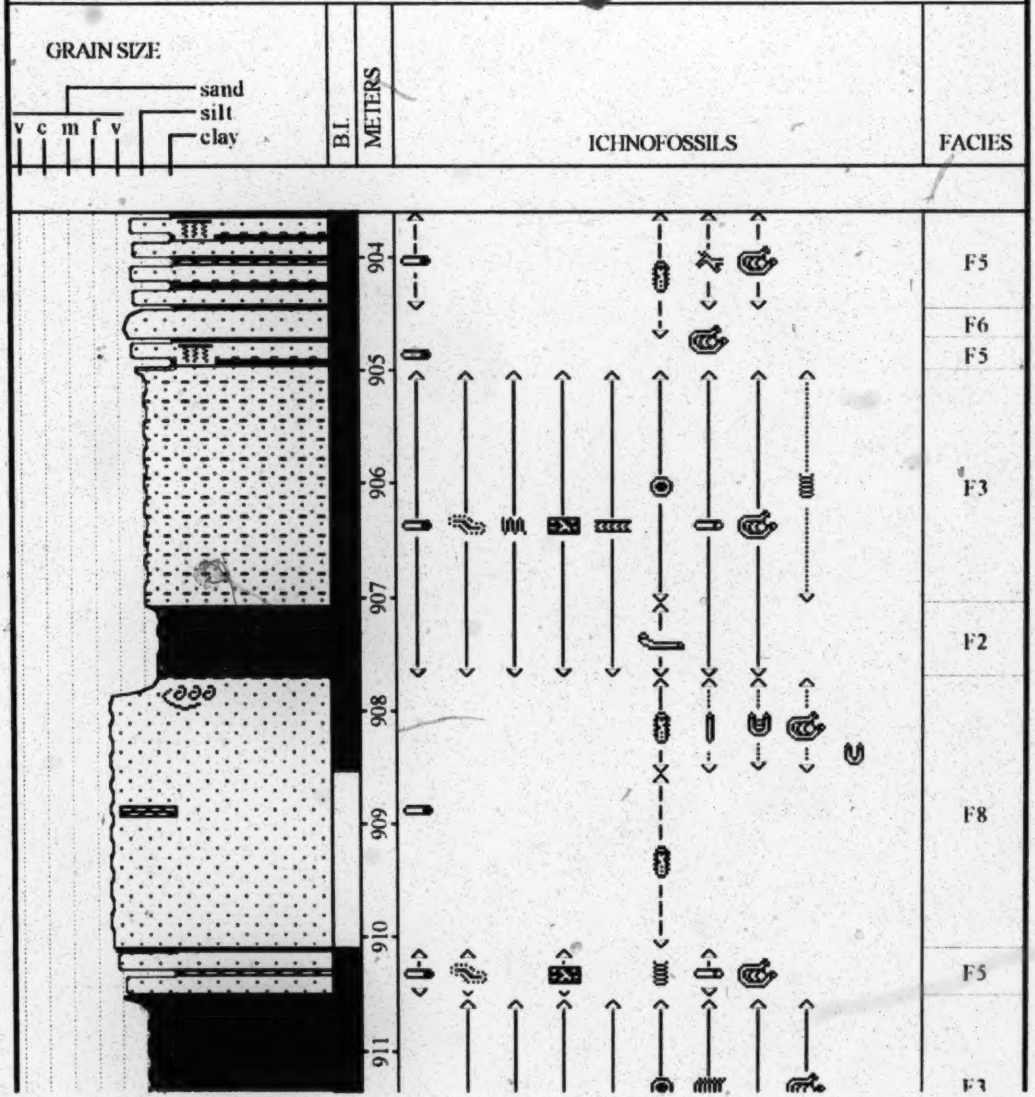

Sd
F4
F1A
F4
F1A

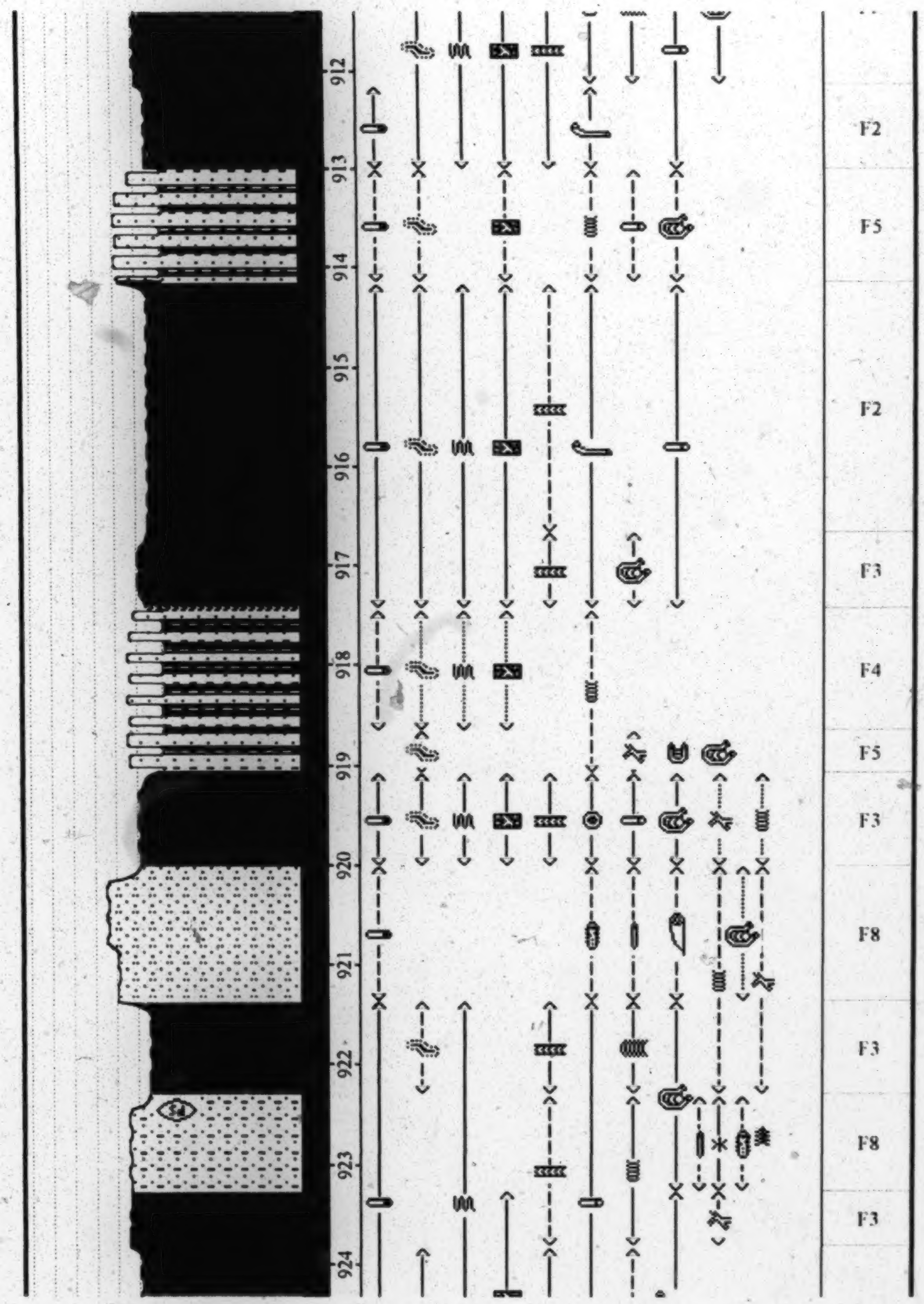
11-01-74-12w6

Date Logged: December 6, 2004

Logged by: © 2005 Scott A. Reid

Ground: 804.10 m KB: 807.70 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
904
905
906
907
908
909
910
911
F5
F6
F5
F3
F2
F8
F5
F3


912
913
914
915
916
917
918
919
920
921
922
923
924
54
F2
F5
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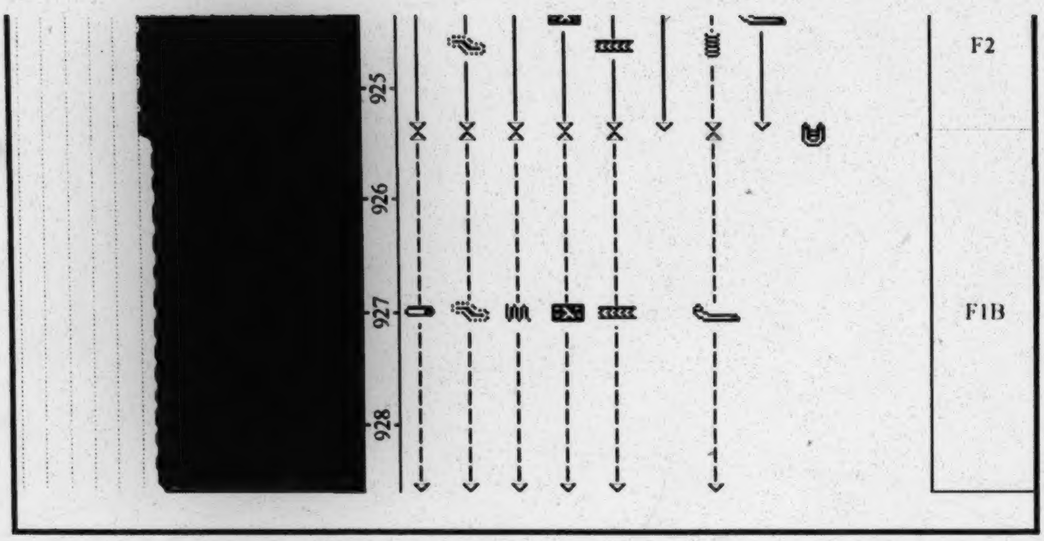
F3
F8
F3
F8
F3

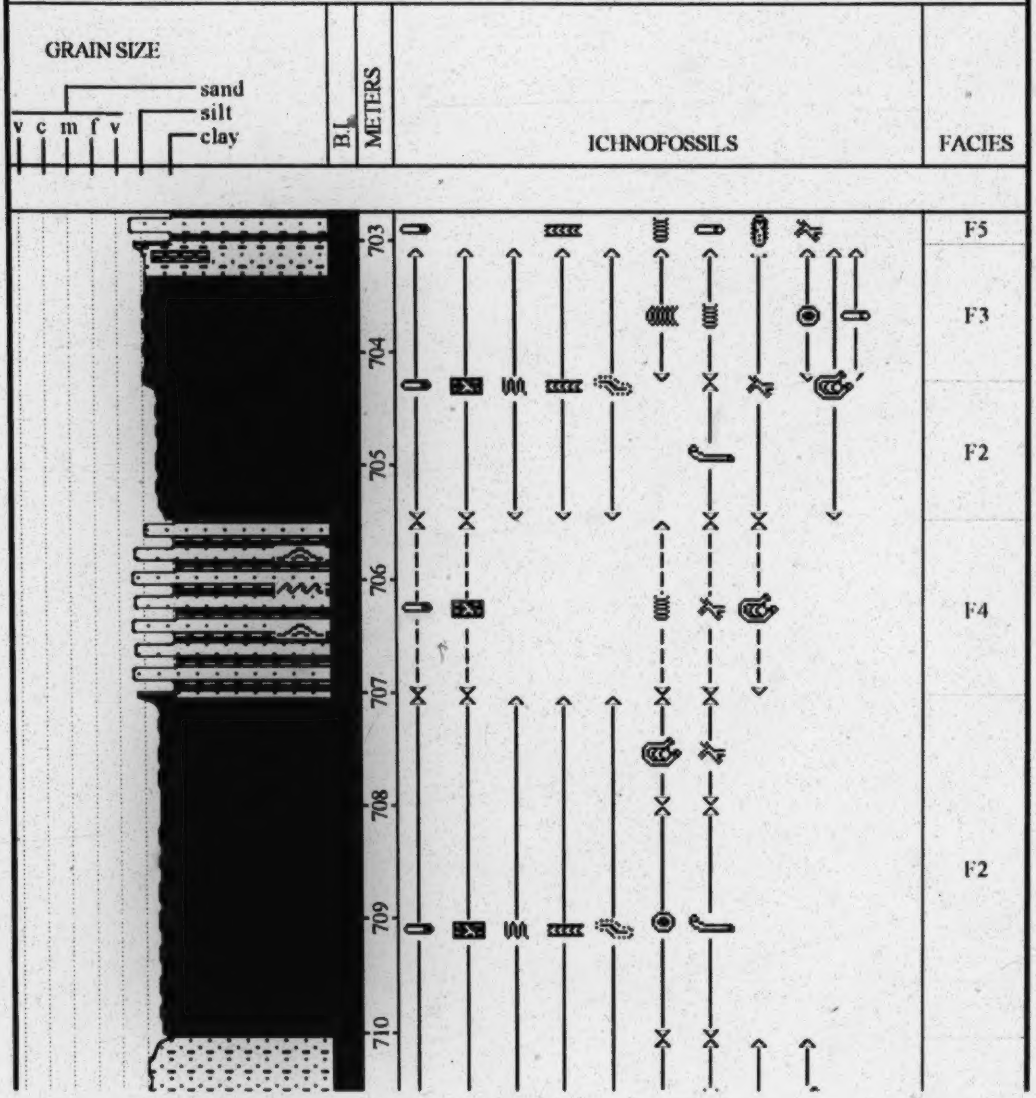

F2
F1B

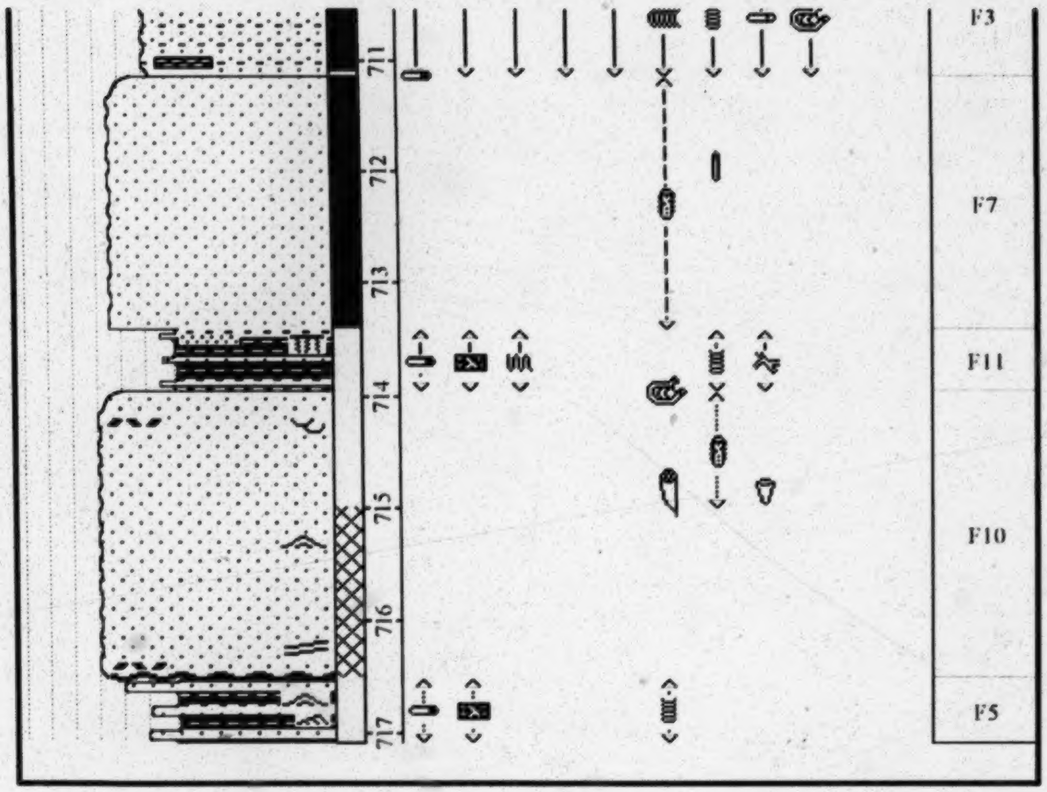
11-04-75-09w6

Date Logged: © 2005 June 17, 2004

Logged by: Scott A. Reid

Ground: 781.50 m KB: 785.40 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
703
704
705
706
707
708
709
710
F5
F3
F2
F4
F2


711
712
713
714
715
716
717
F3
F7
F11
F10
F5

11-09-75-9w6

Date Logged: August 20, 2003

Logged by: © 2005 Scott A. Reid

Ground: 795.00 m KB: 798.50 m

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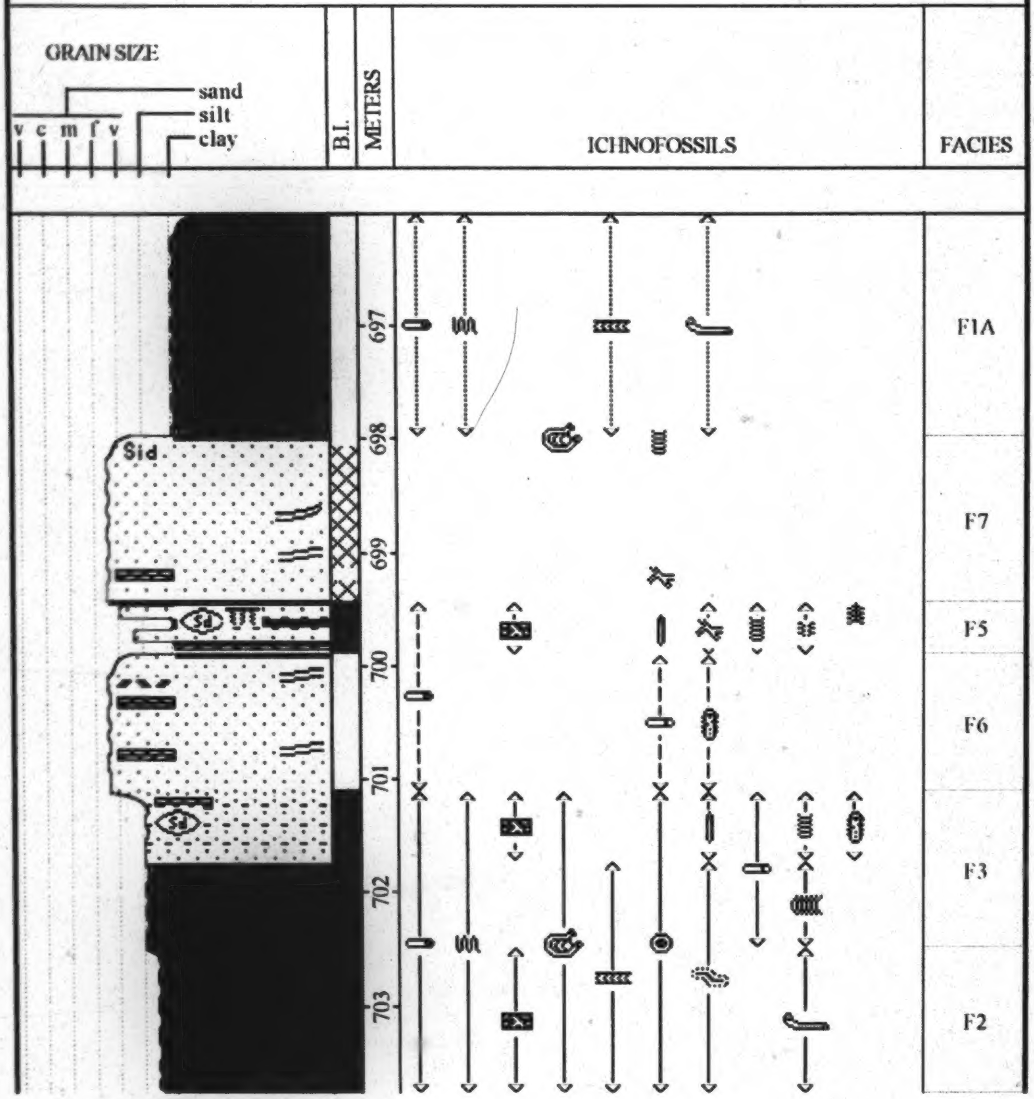
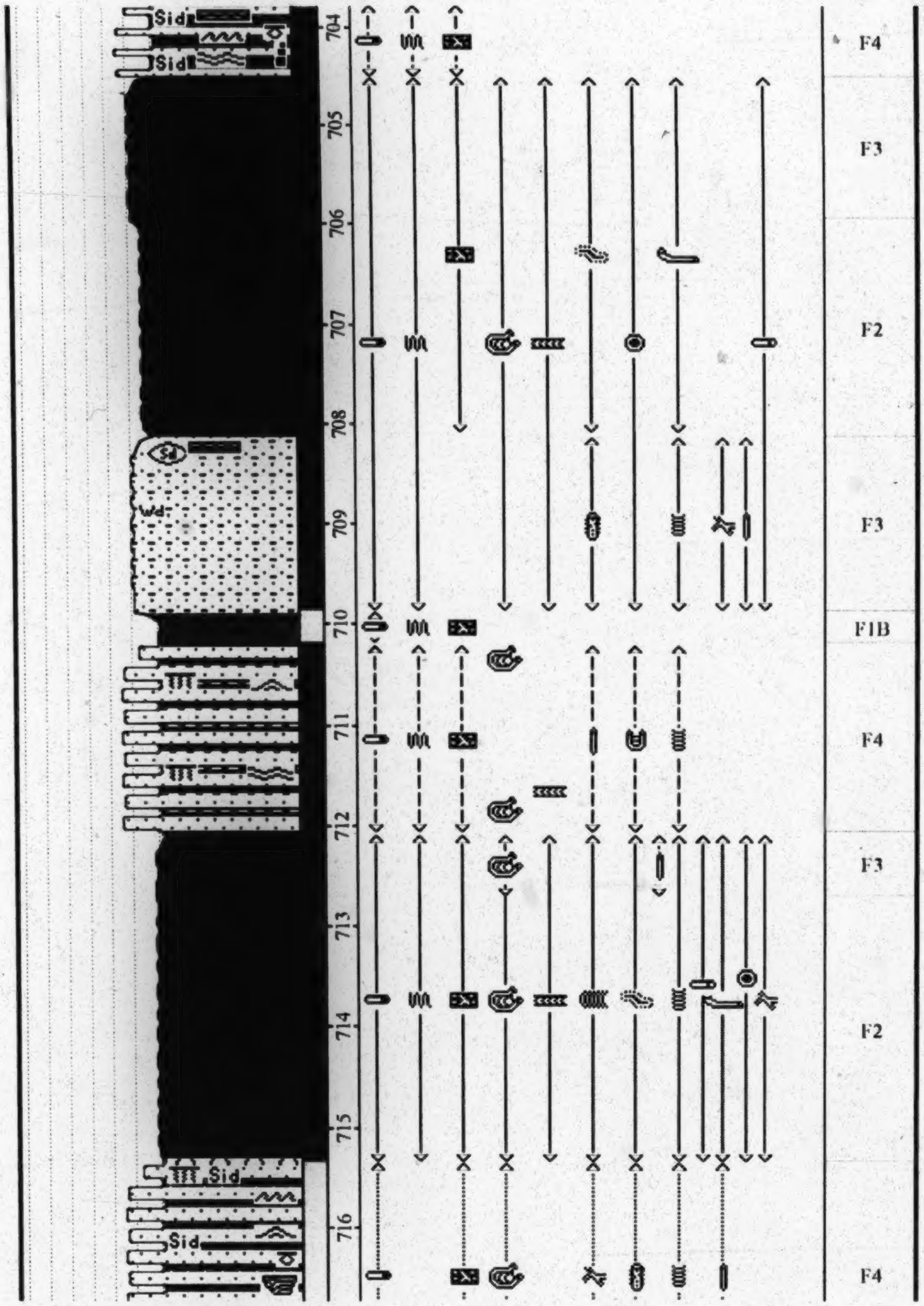
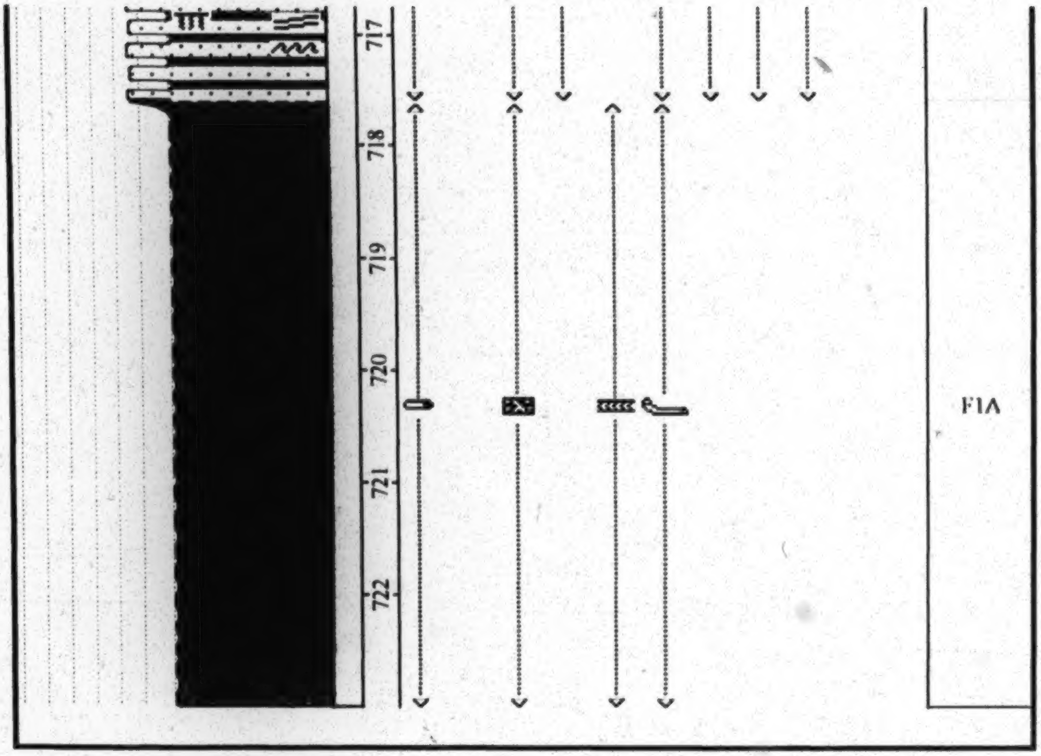

GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
697
698
699
700
701
702
703
Sid
Sd
Sd
F1A
F7
F5
F6
F3
F2


Sid
Sid
Sd
Wd
Sid
Sid
704
705
706
707
708
709
710
711
712
713
714
715
716
F4
F3
F2
F3
F1B
F4
F3
F2
F4

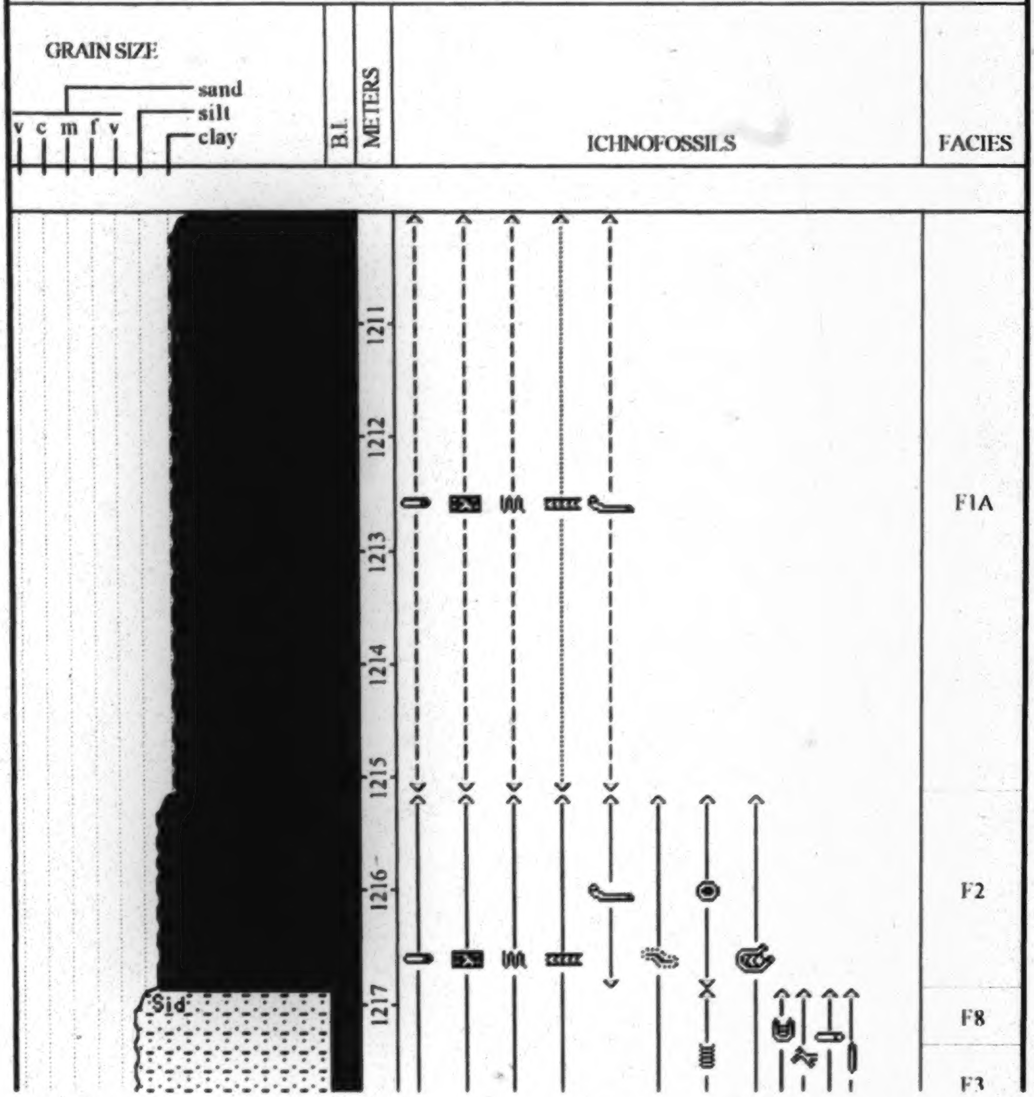

F1A

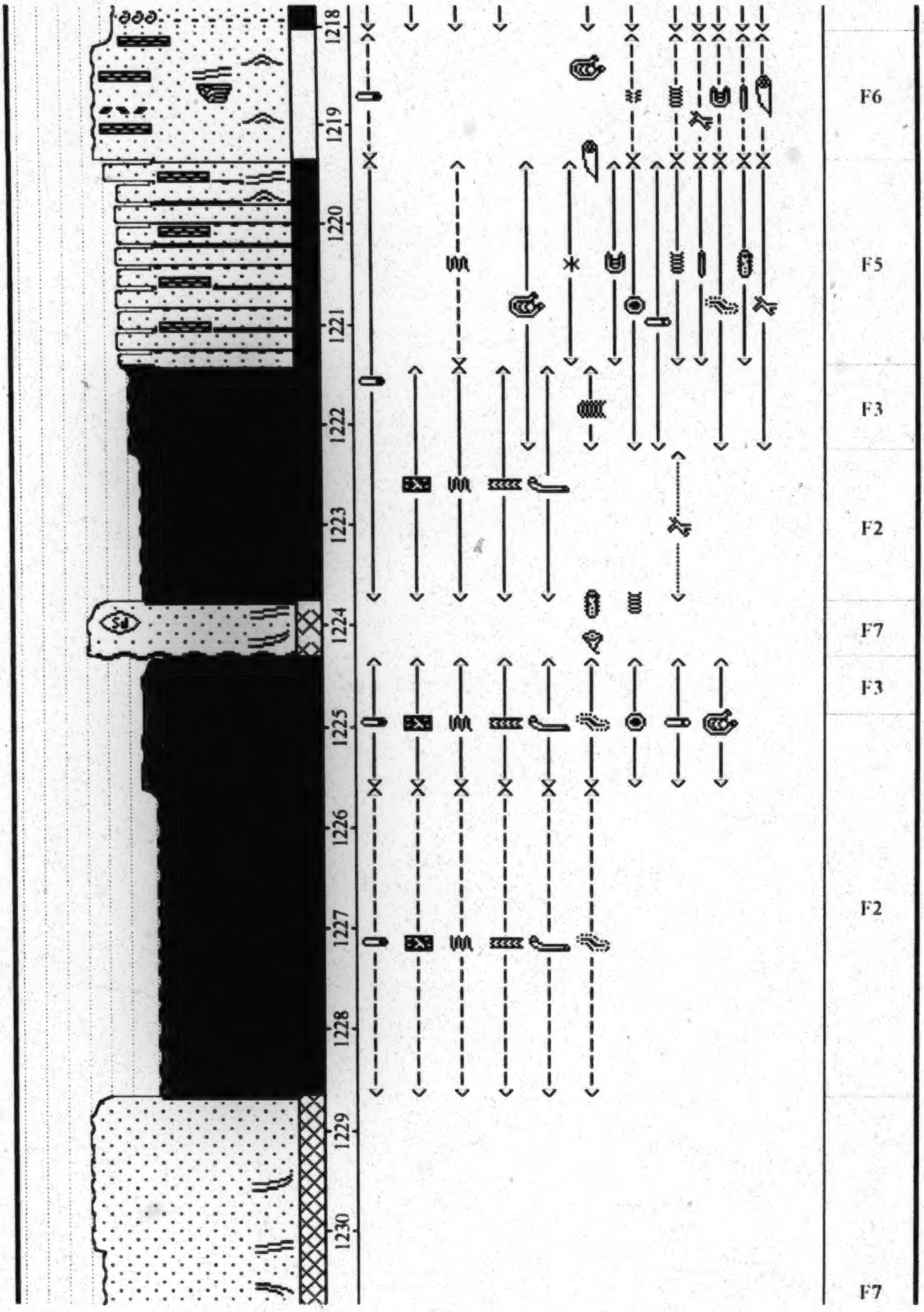
11-33-71-12w6

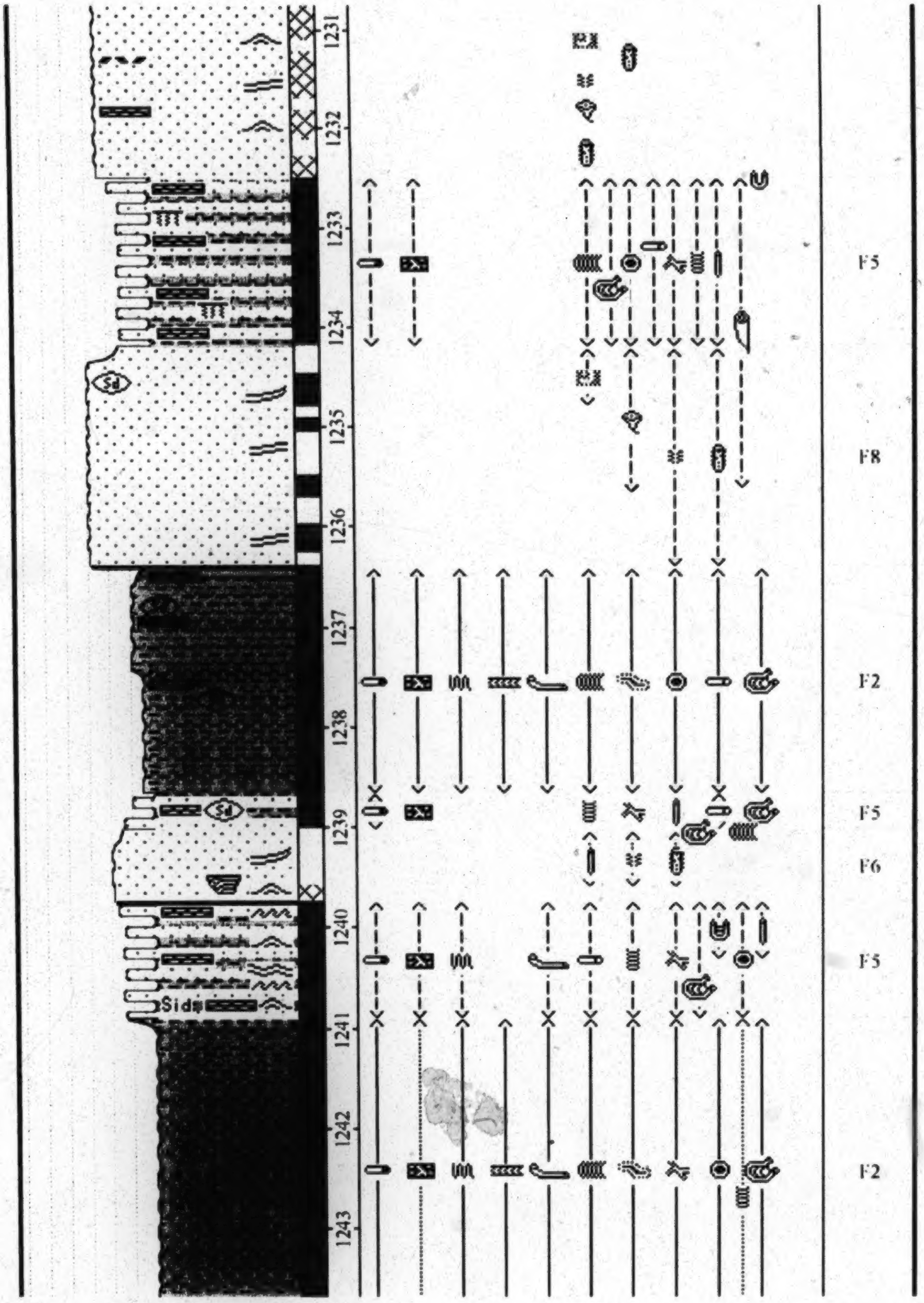
Date Logged: June 8, 2004

Logged by: © 2005 Scott A. Reid

Ground: 811.70 m KB: 815.80 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
1211
1212
1213
1214
1215
1216
1217
Sid
F1A
F2
F8
F3


F6
F5
F3
F2
F7
F3
F2
F7


1231
1232
1233
1234
1235
1236
1237
1238
1239
1240
1241
1242
1243
Sd
Sd
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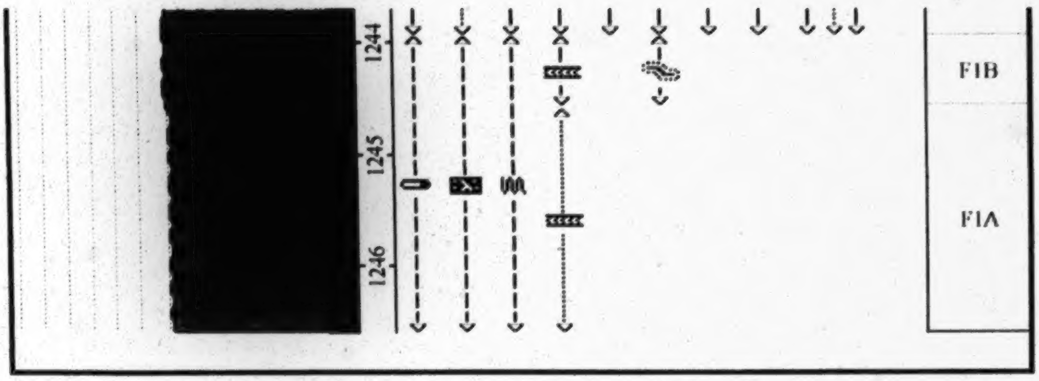
F2
F5
F6
F5
F2

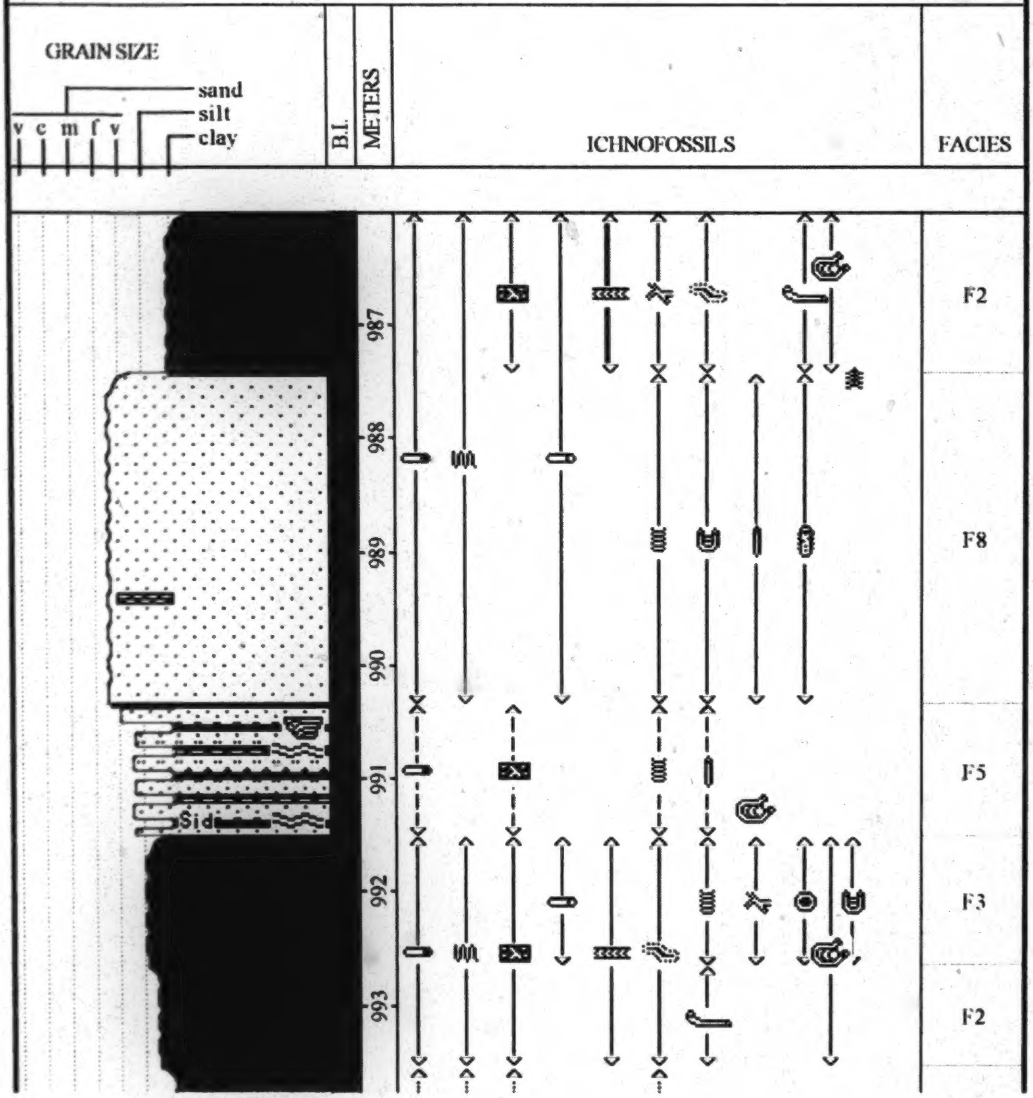

F1B
F1A

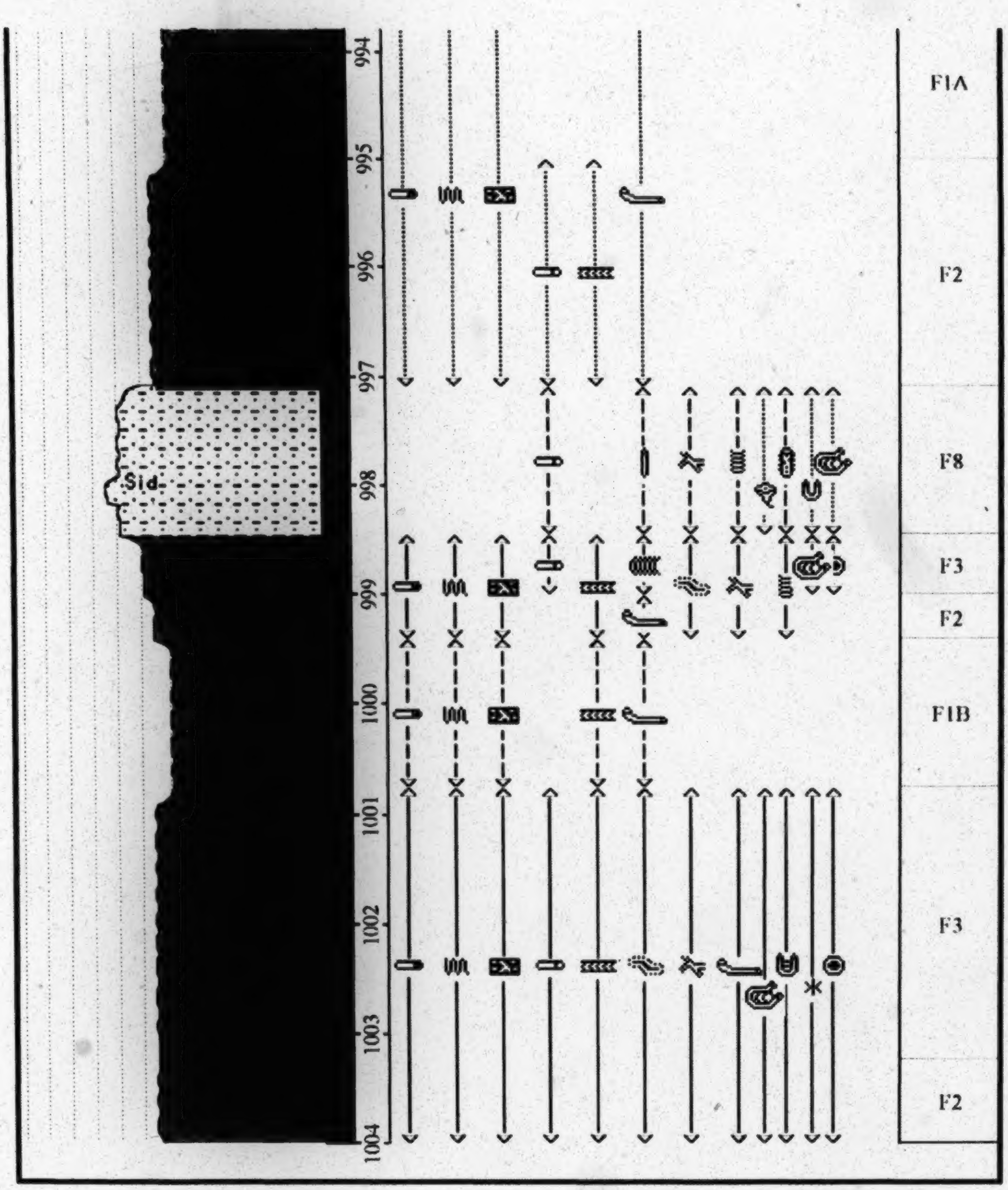
13-13-73-13w6

Date Logged: June 24, 2004

Logged by: © 2005 Scott A. Reid

Ground: 791.70 m KB: 796.00 m




994
995
996
997
998
999
1000
1001
1002
1003
1004
Sid.
F1A
F2
F8
F3
F2
F1B
F3
F2

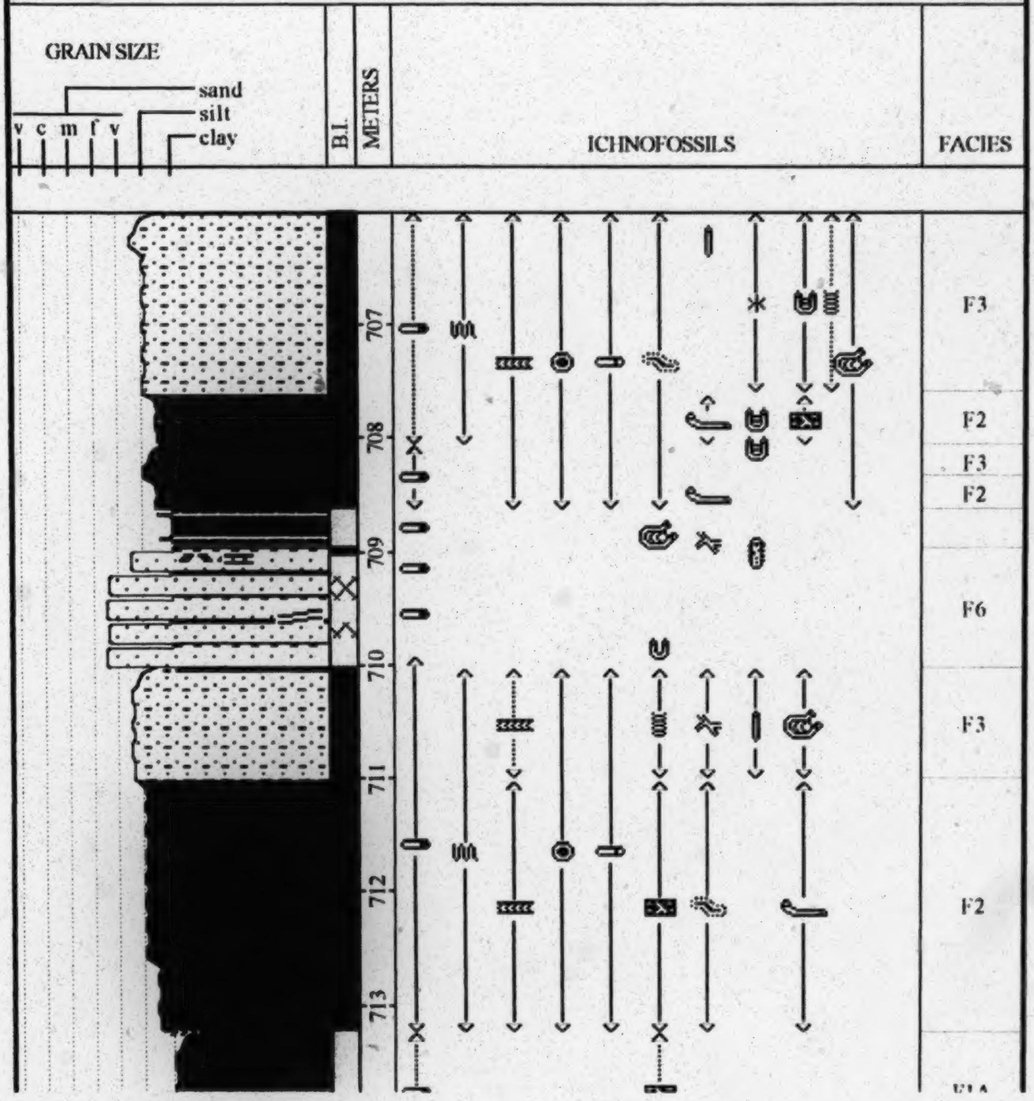
14-10-76-10w6

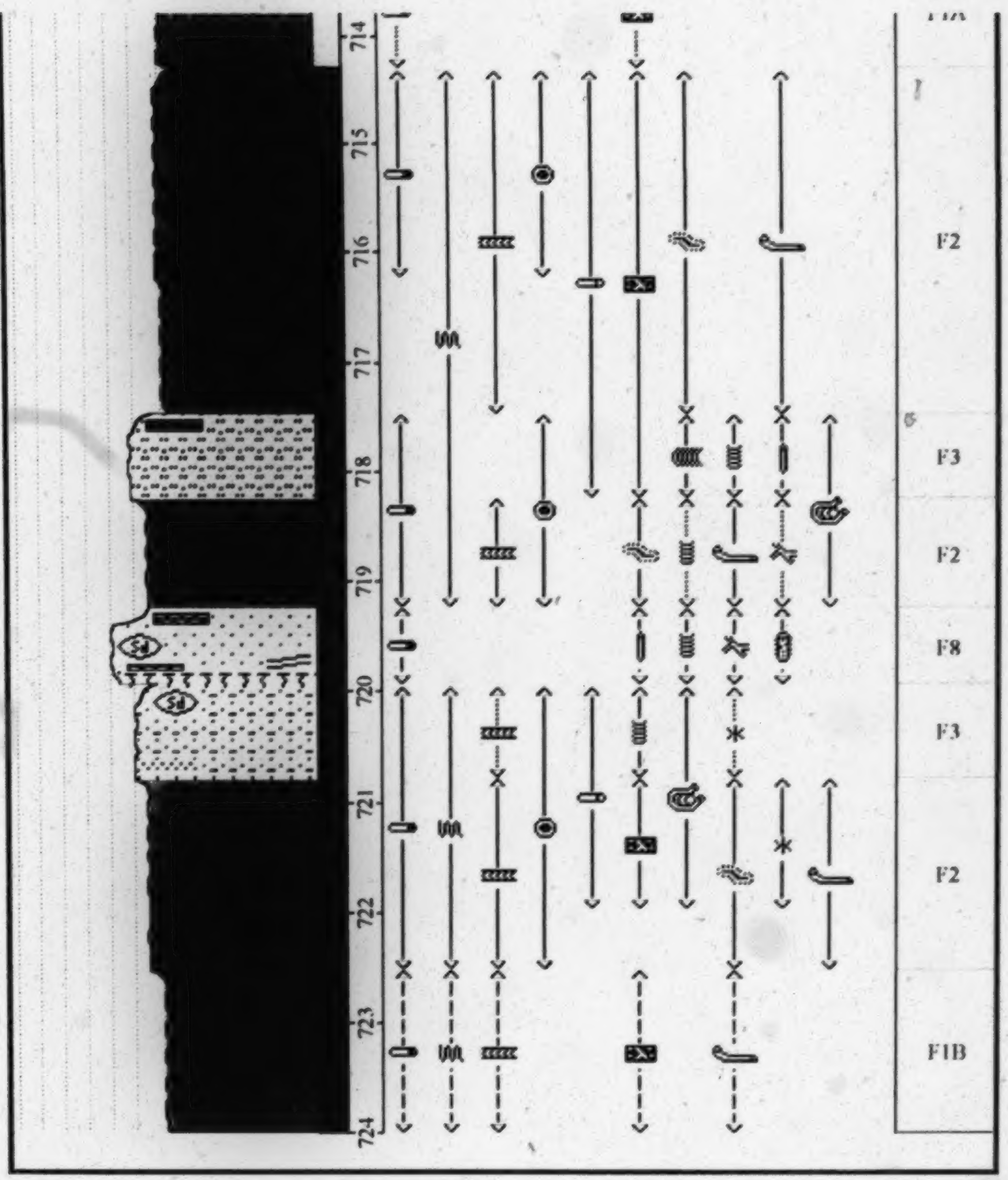
Date Logged: February 18, 2004

Logged by: © 2005 Scott A. Reid

Ground: 902.90 m KB: 906.20 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
707
708
709
710
711
712
713
F3
F2
F3
F2
F6
F3
F2


714
715
716
717
718
719
720
721
722
723
724
Sd
Sd
F1A
F2
F3
F2
F8
F3
F2
F1B

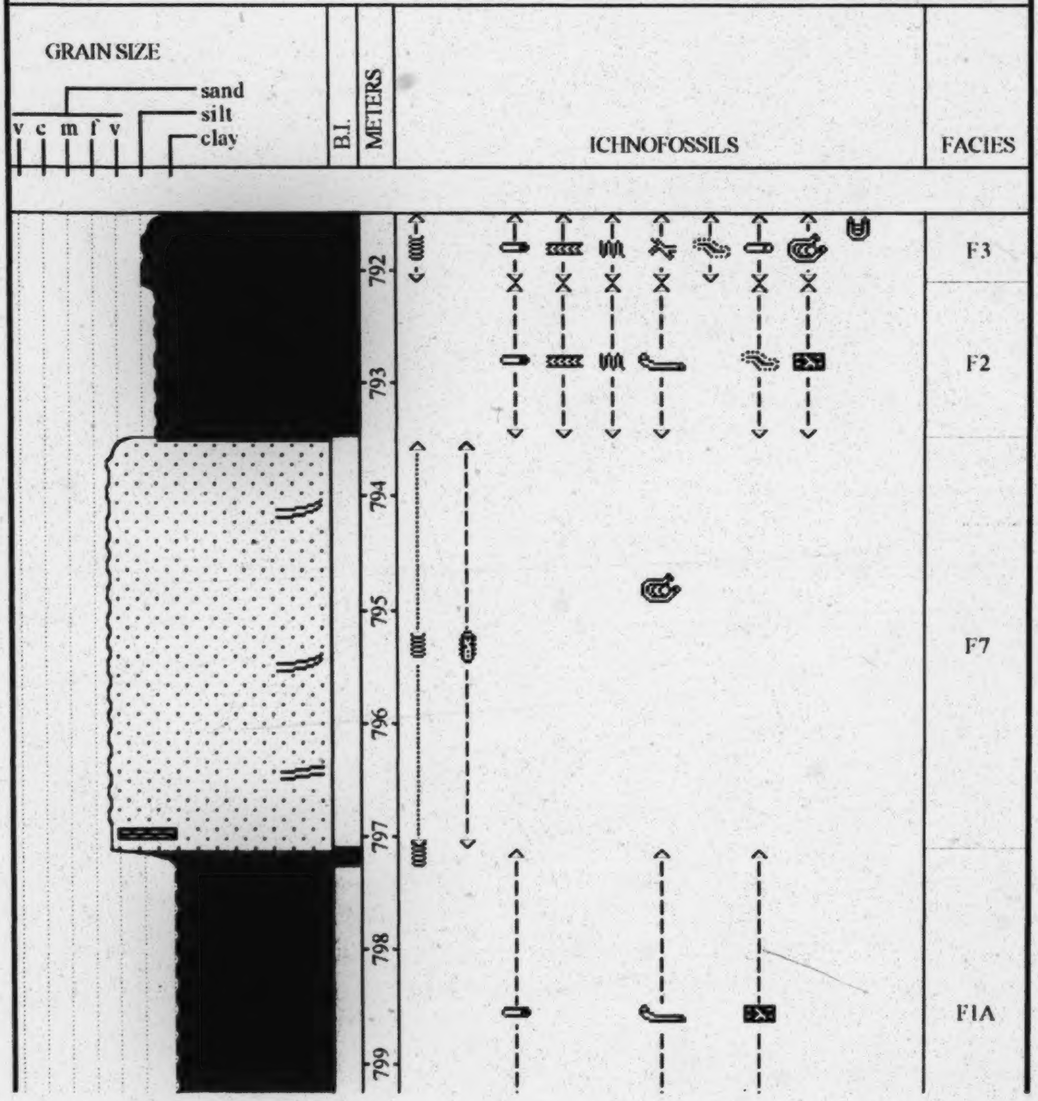
14-11-75-12w6

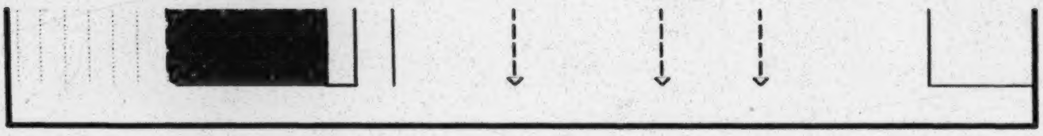
Date Logged: July 28, 2003

Logged by: © 2005 Scott A. Reid

Ground: 848.70 m KB: 853.40 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
792
793
794
795
796
797
798
799
F3
F2
F7
F1A

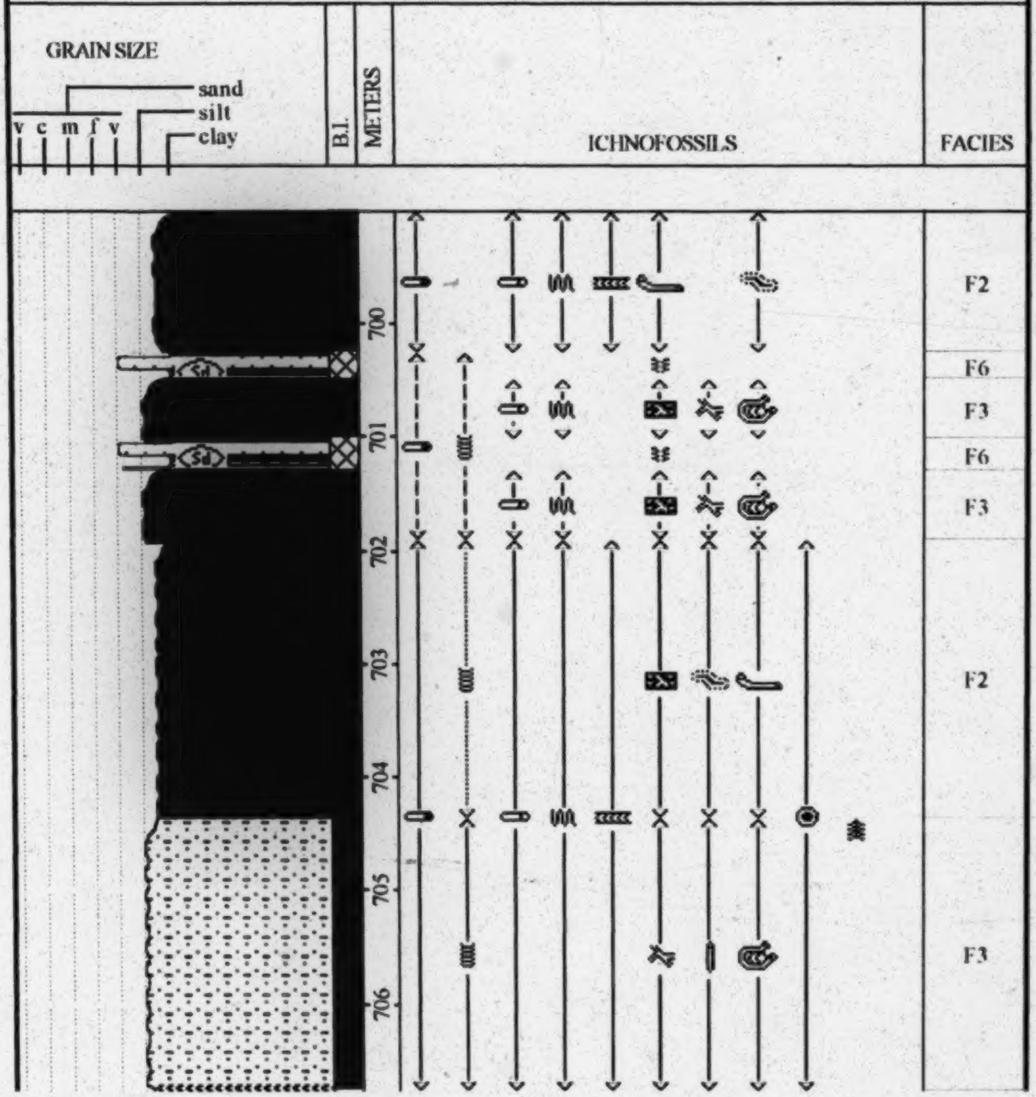


14-24-75-10w6

Date Logged: June 20, 2004

Logged by: ©2005 Scott A. Reid

Ground: 819.80 m KB: 822.80 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
Sd
Sd
700
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702
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704
705
706
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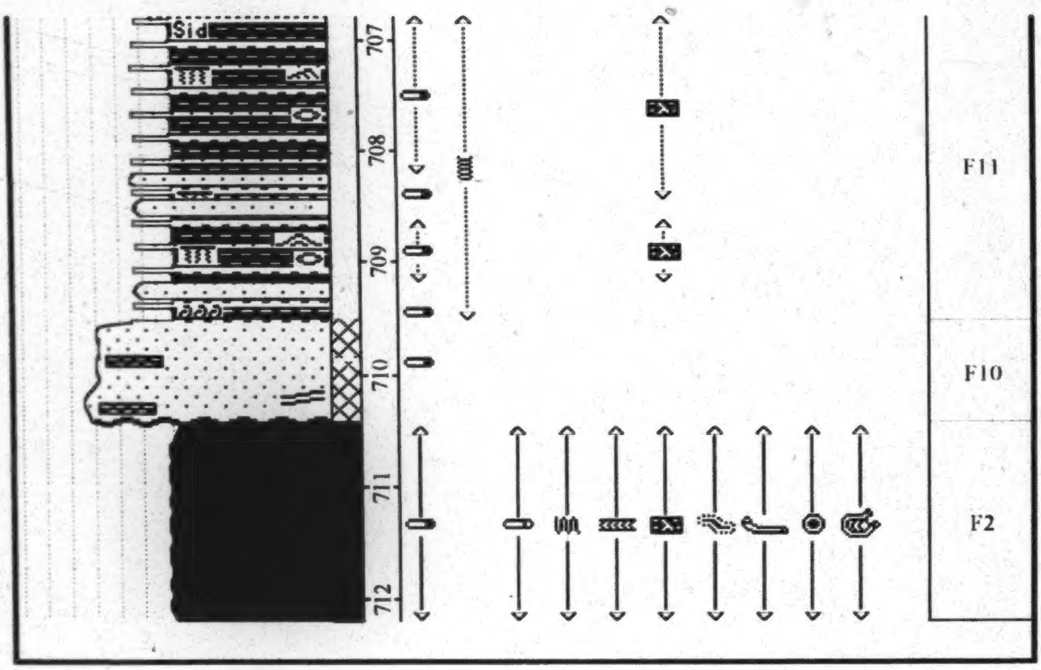
F3
F6
F3
F2
F3

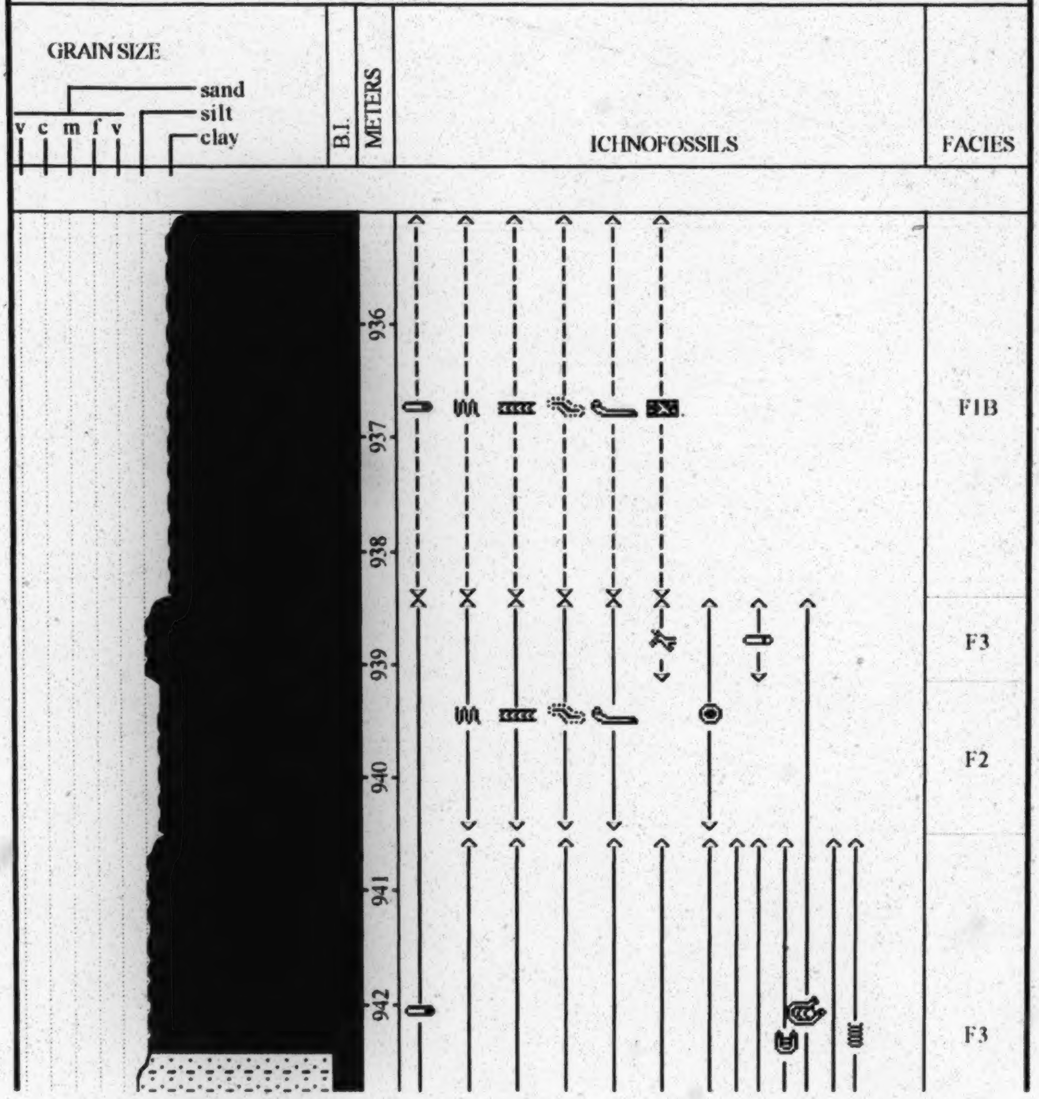

Sid
F11
F10
F2

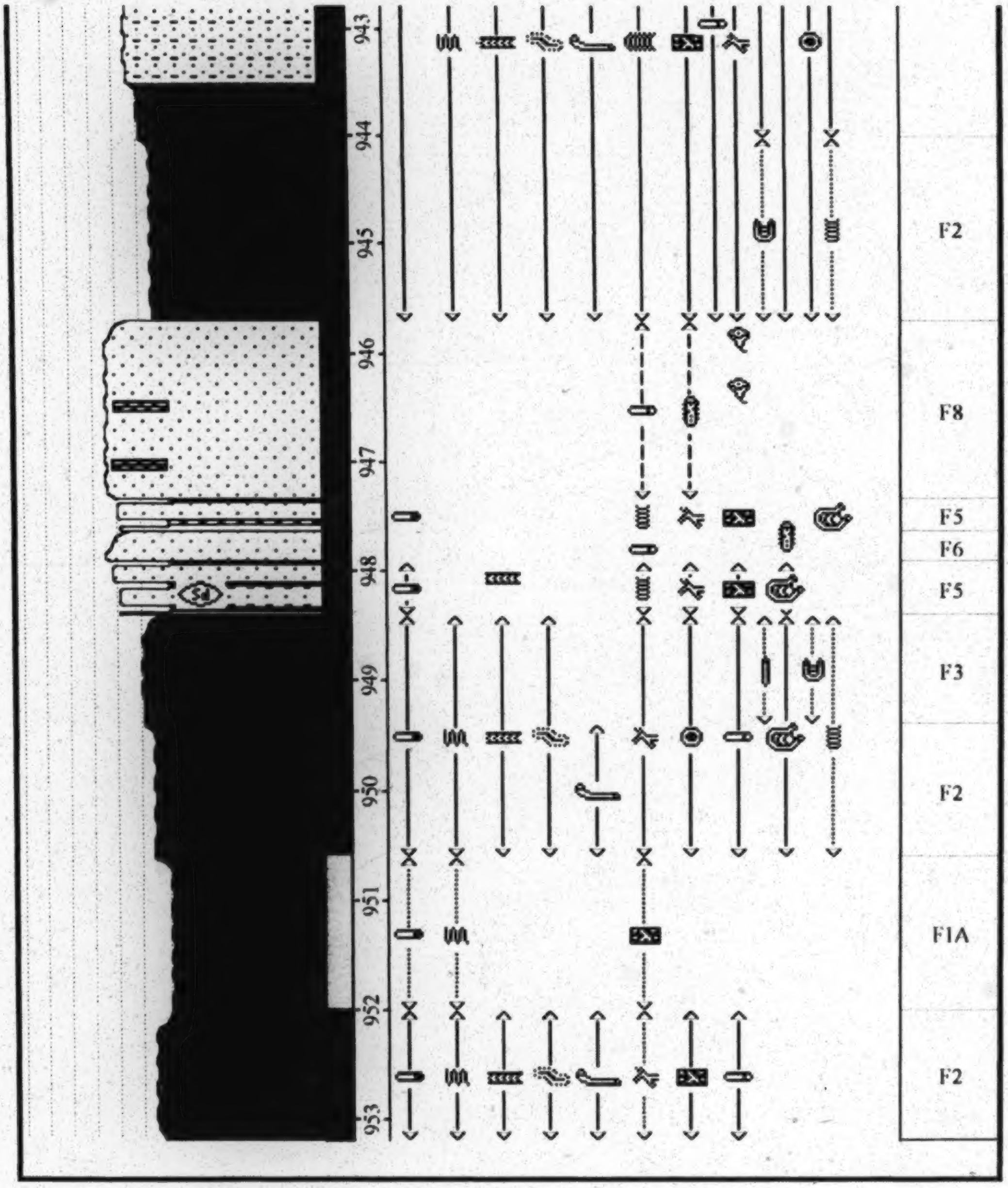
14-25-73-13w6

Date Logged: June 14, 2004

Logged by: © 2005 Scott A. Reid

Ground: 802.10 m KB: 806.70 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
936
937
938
939
940
941
942
F1B
F3
F2
F3


943
944
945
946
947
948
949
950
951
952
953
Sd
F2
F8
F5
F6
F5
F3
F2
F1A
F2

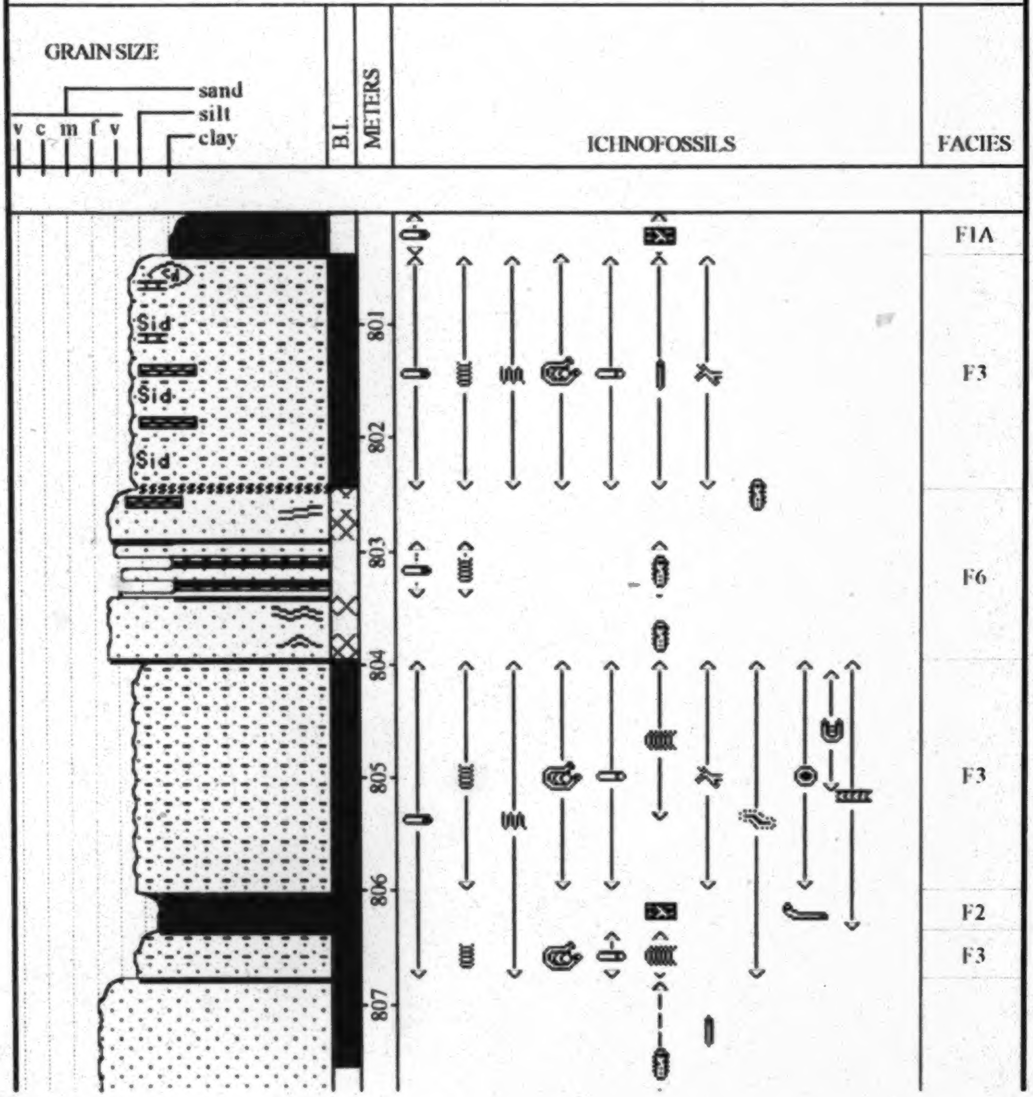
14-25-74-12w6

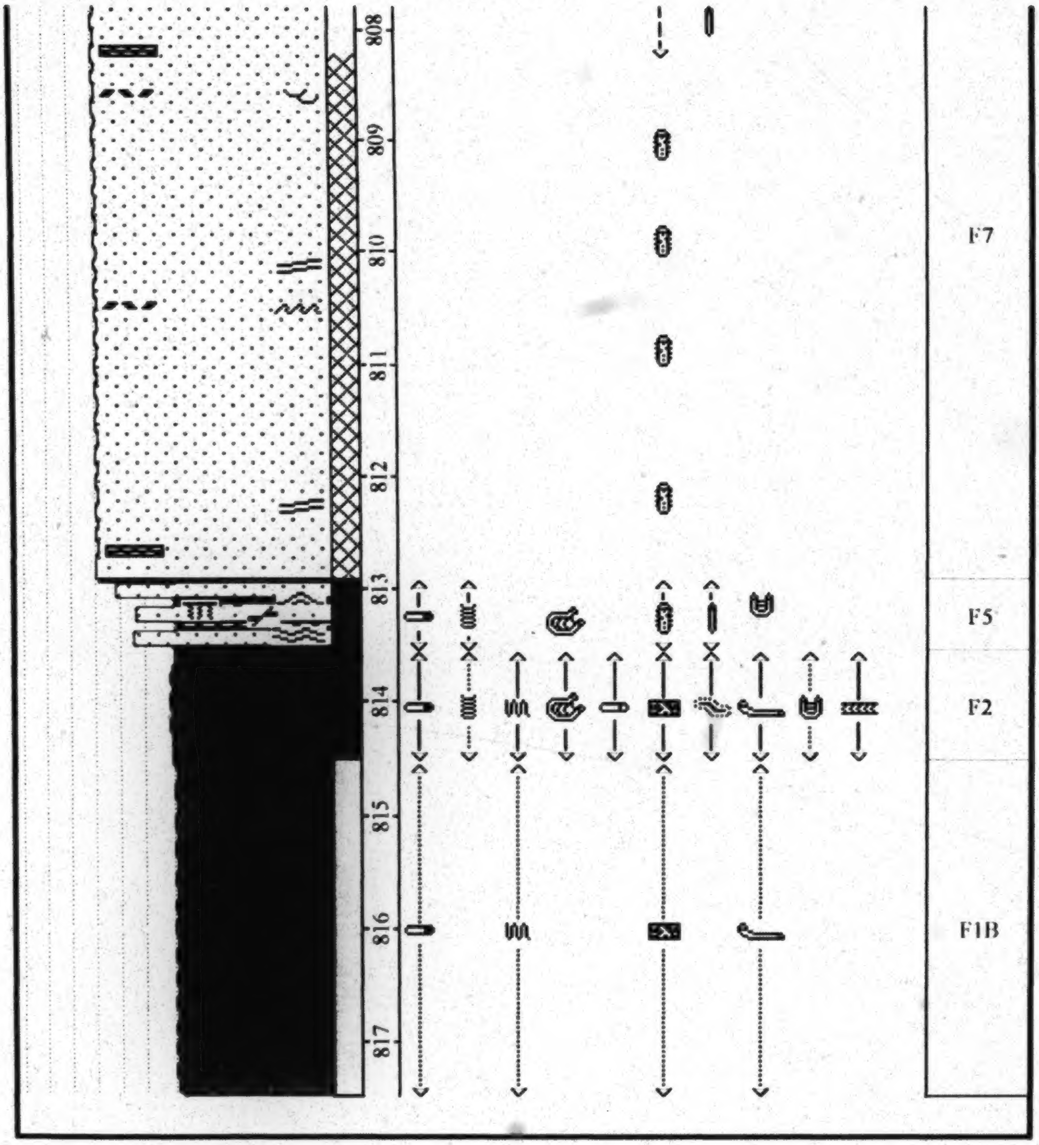
Date Logged: June 16, 2003

Logged by: © 2005 Scott A. Reid

Ground: 798.80 m KB: 801.80 m

Ichnology Research Group


GRAIN SIZE
v c m f v
sand
silt
clay
B.I.
METERS
ICHNOFOSSILS
FACIES
Sid
Sid
Sid
801
802
803
804
805
806
807
F1A
F3
F6
F3
F2
F3


F7
F5
F2
F1B

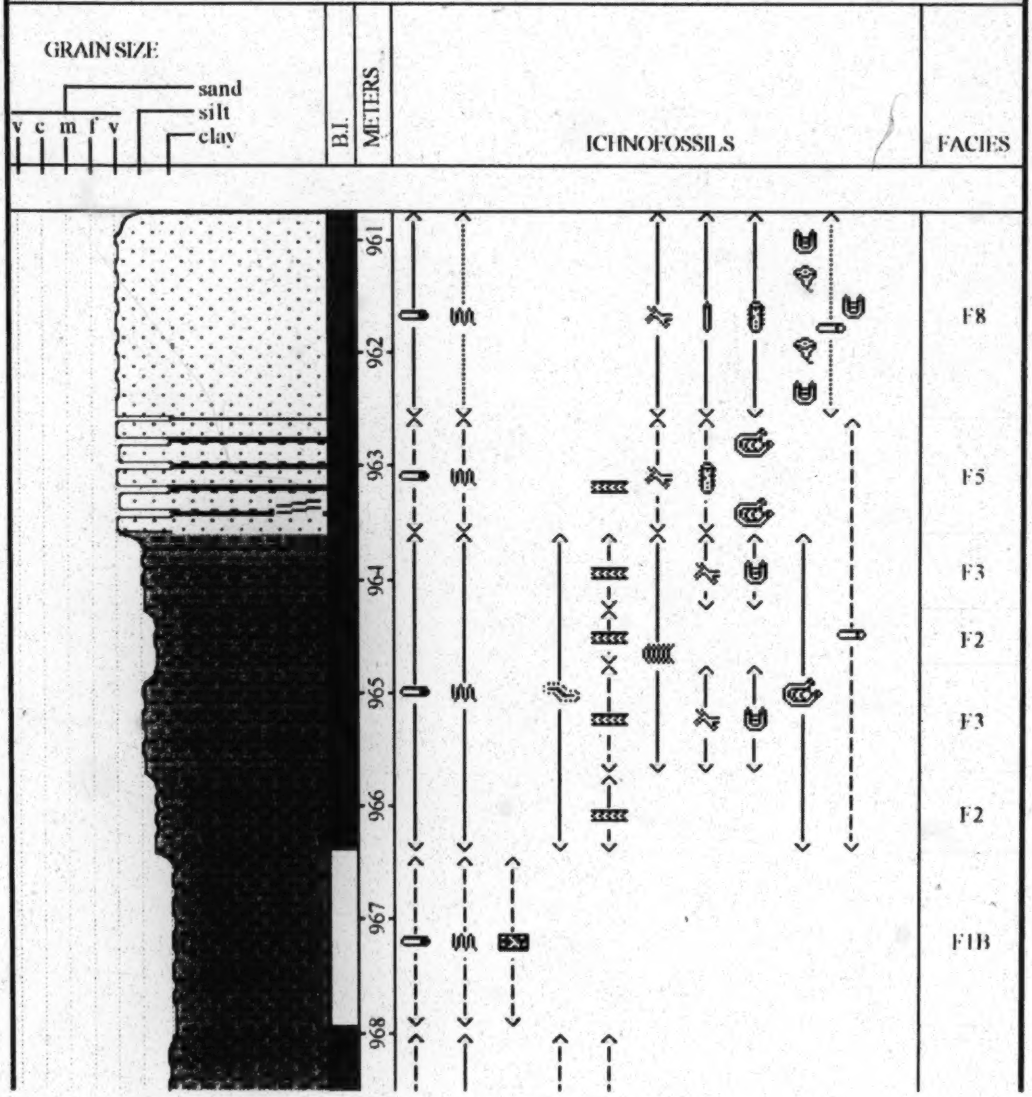
14-27-73-13w6

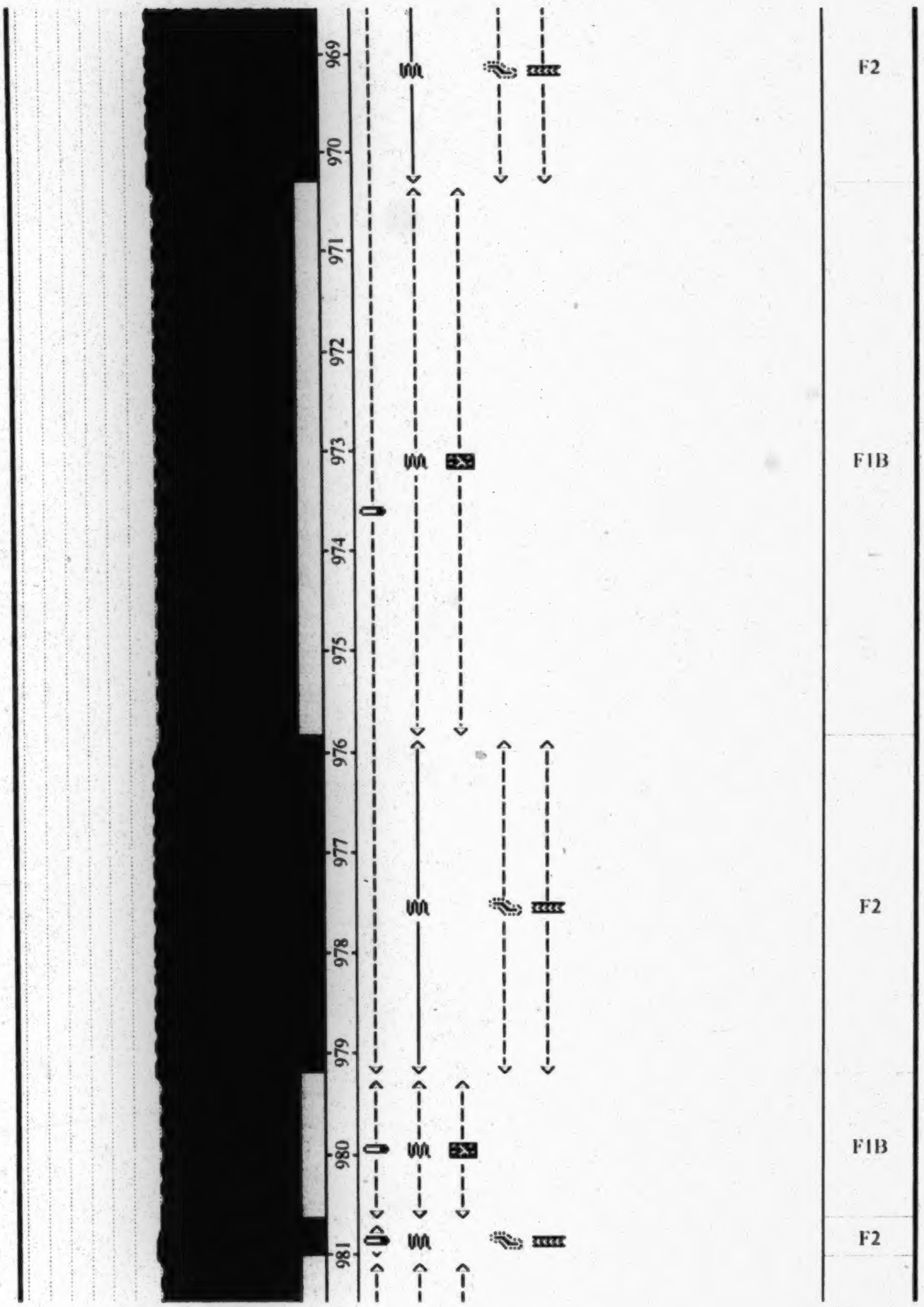
Date Logged: June 15, 2004

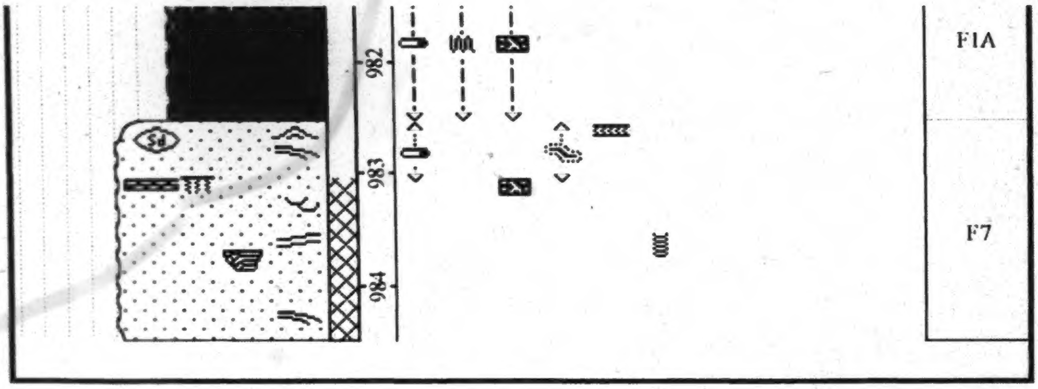
Logged by: © 2005 Scott A. Reid

Ground: 800.20 m KB: 804.30 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
961
962
963
964
965
966
967
968
F8
F5
F3
F2
F3
F2
F1B


F2
F1B
F2
F1B
F2

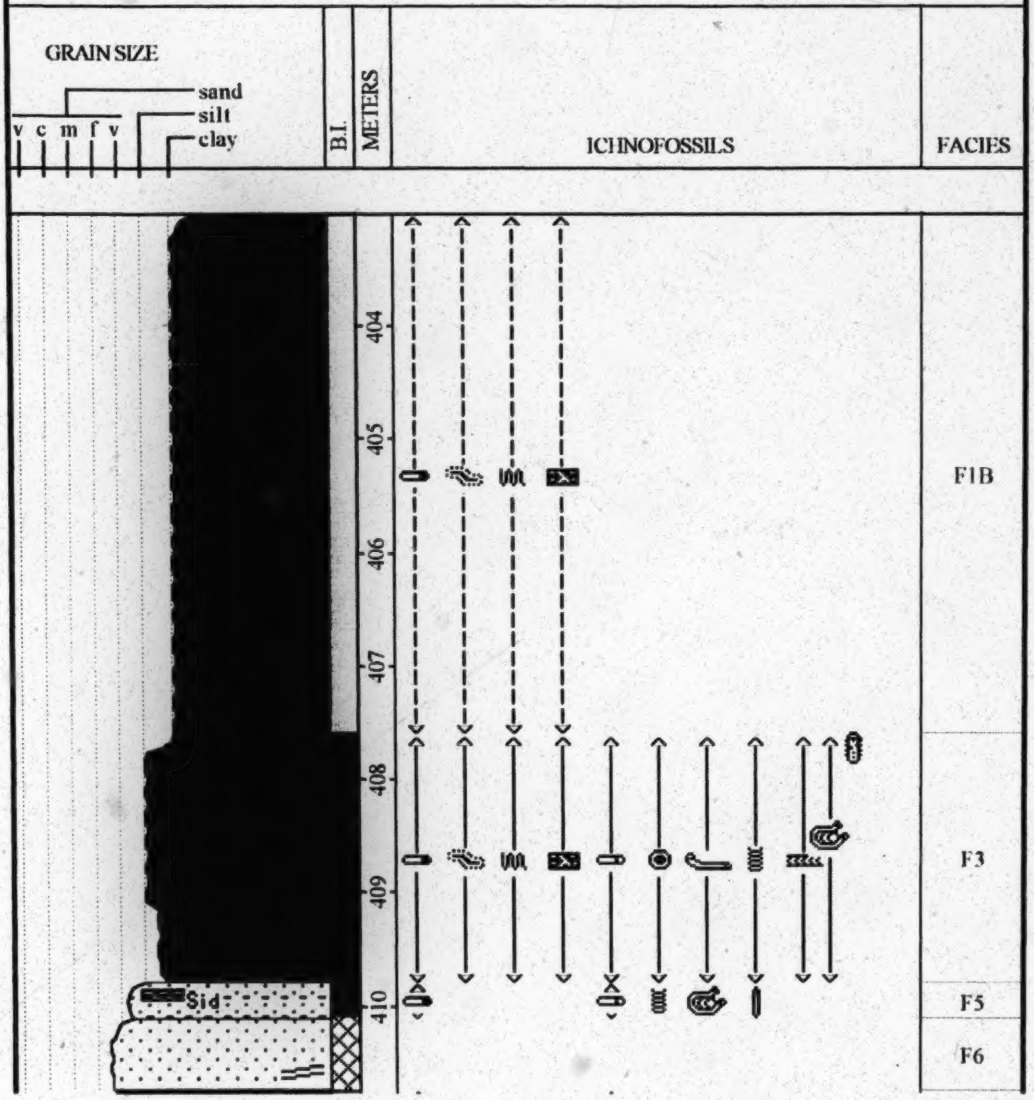

F1A
F7

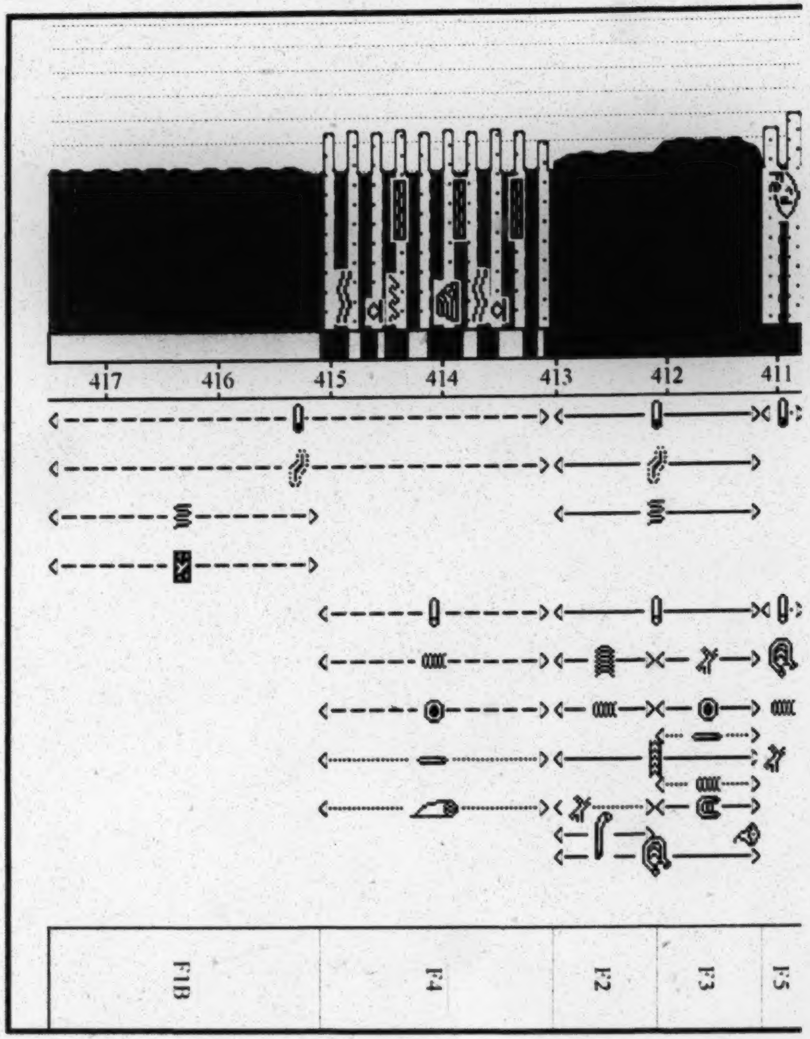
14-30-77-6w6

Date Logged: June 20, 2003

Logged by: ©2005 Scott A. Reid

Ground: 722.80 m KB: 726.80 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
404
405
406
407
408
409
410
Sid
F1B
F3
F5
F6

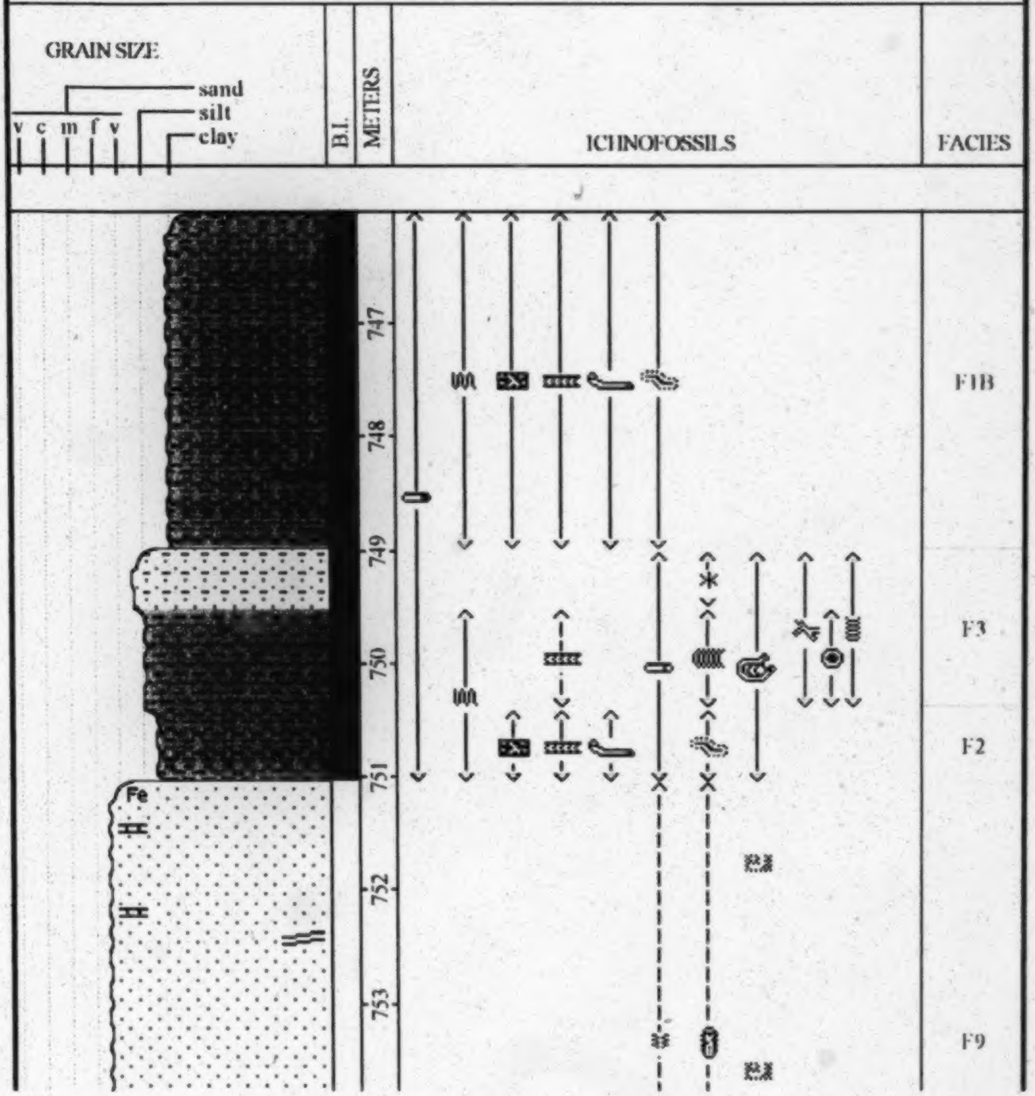

Fe
417
416
415
414
413
412
411
F1B
F4
F2
F3
F5

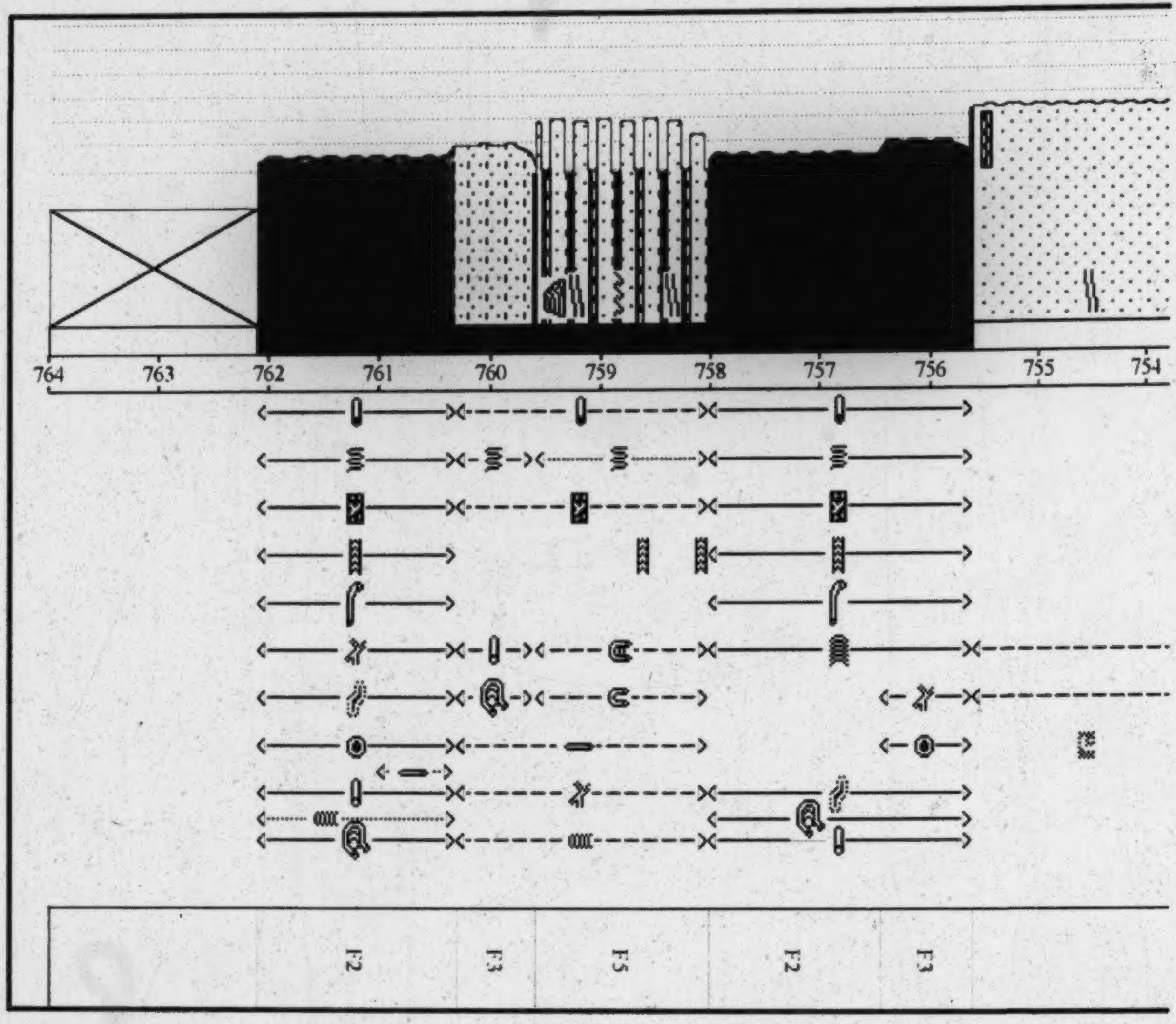
14-31-74-10w6

Date Logged: August 8, 2003

Logged by: © 2005 Scott A. Reid

Ground: 784.80 m KB: 788.70 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
747
748
749
750
751
752
753
Fe
F1B
F3
F2
F9

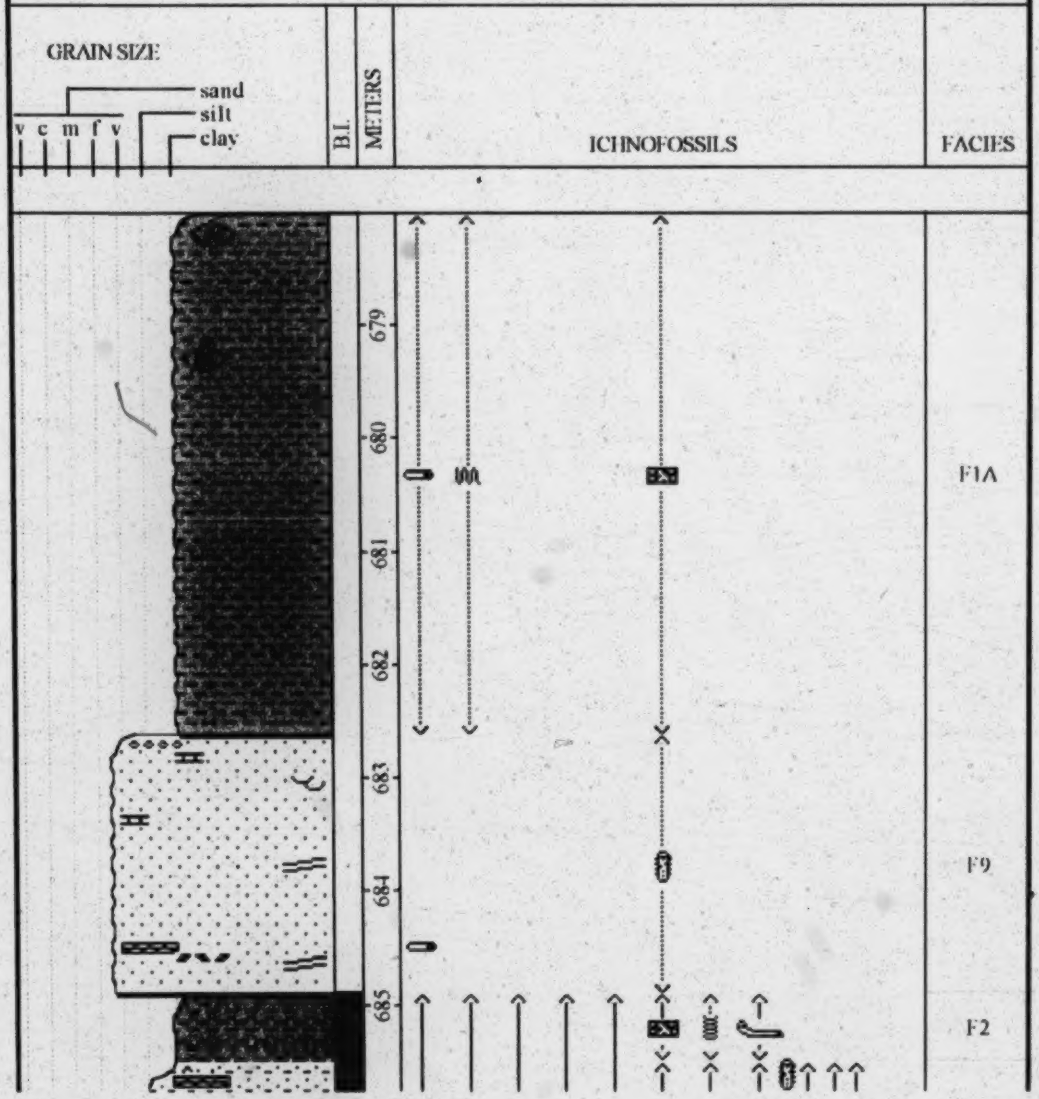

F2
F3
F5
F2
F3

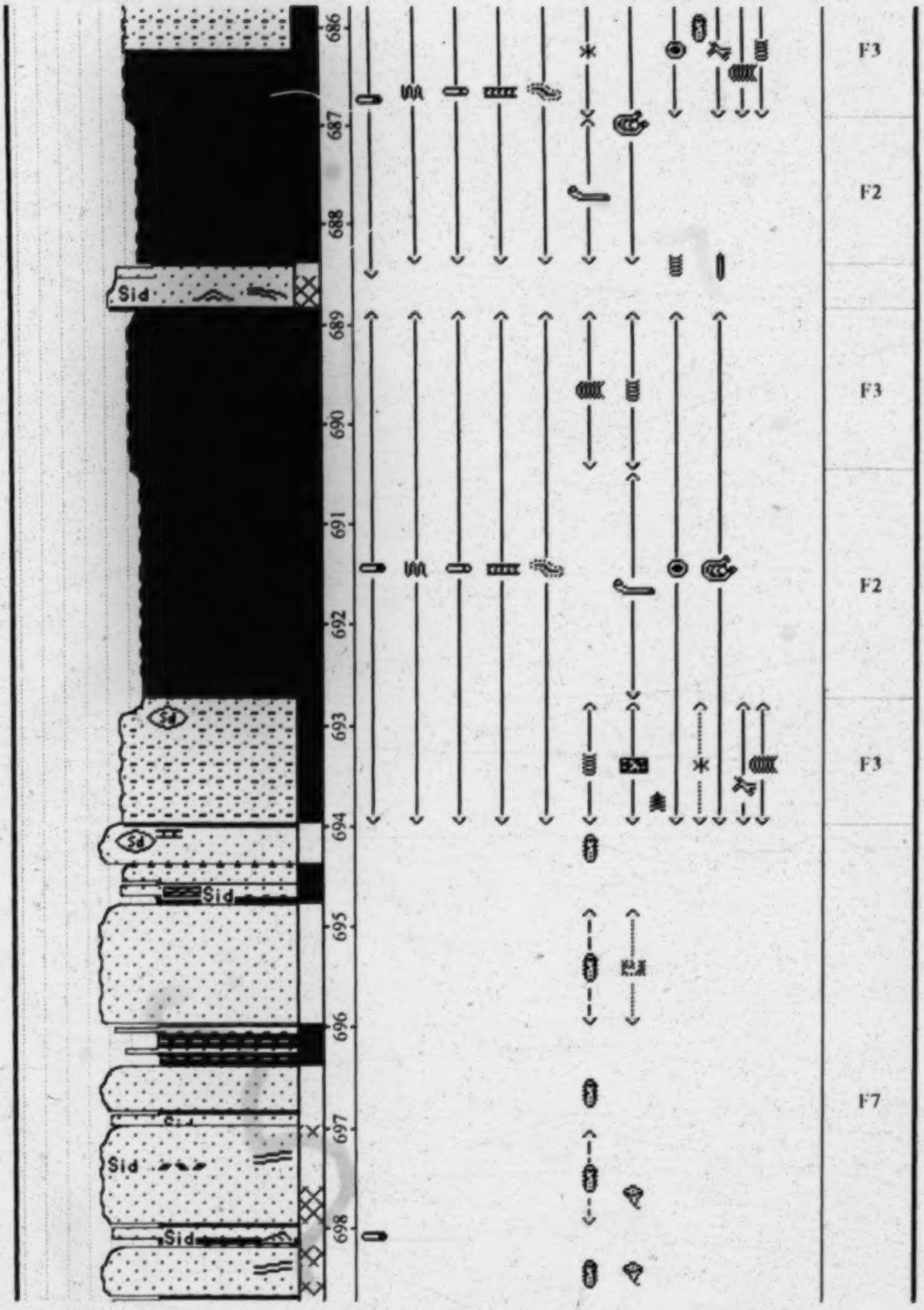
14-32-74-9w6

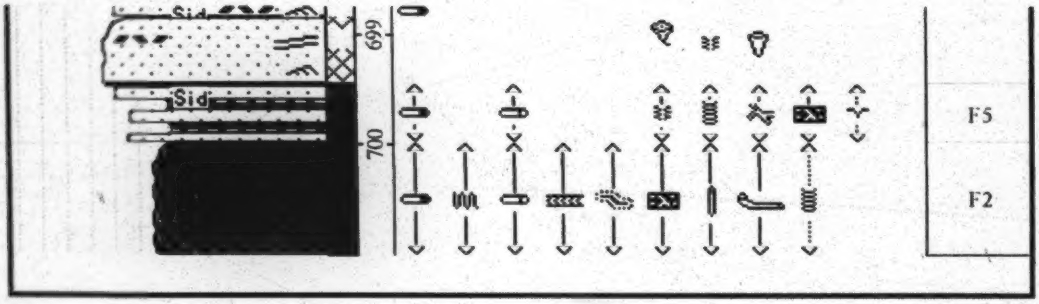
Date Logged: February 20, 2004

Logged by: © 2005 Scott A. Reid

Ground: 752.50 m KB: 756.00 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
679
680
681
682
683
684
685
F1A
F9
F2


686
687
688
689
690
691
692
693
694
695
696
697
698
Sid
Sid
Sid
Sid
Sid
Sid
F3
F2
F3
F2
F3
F7

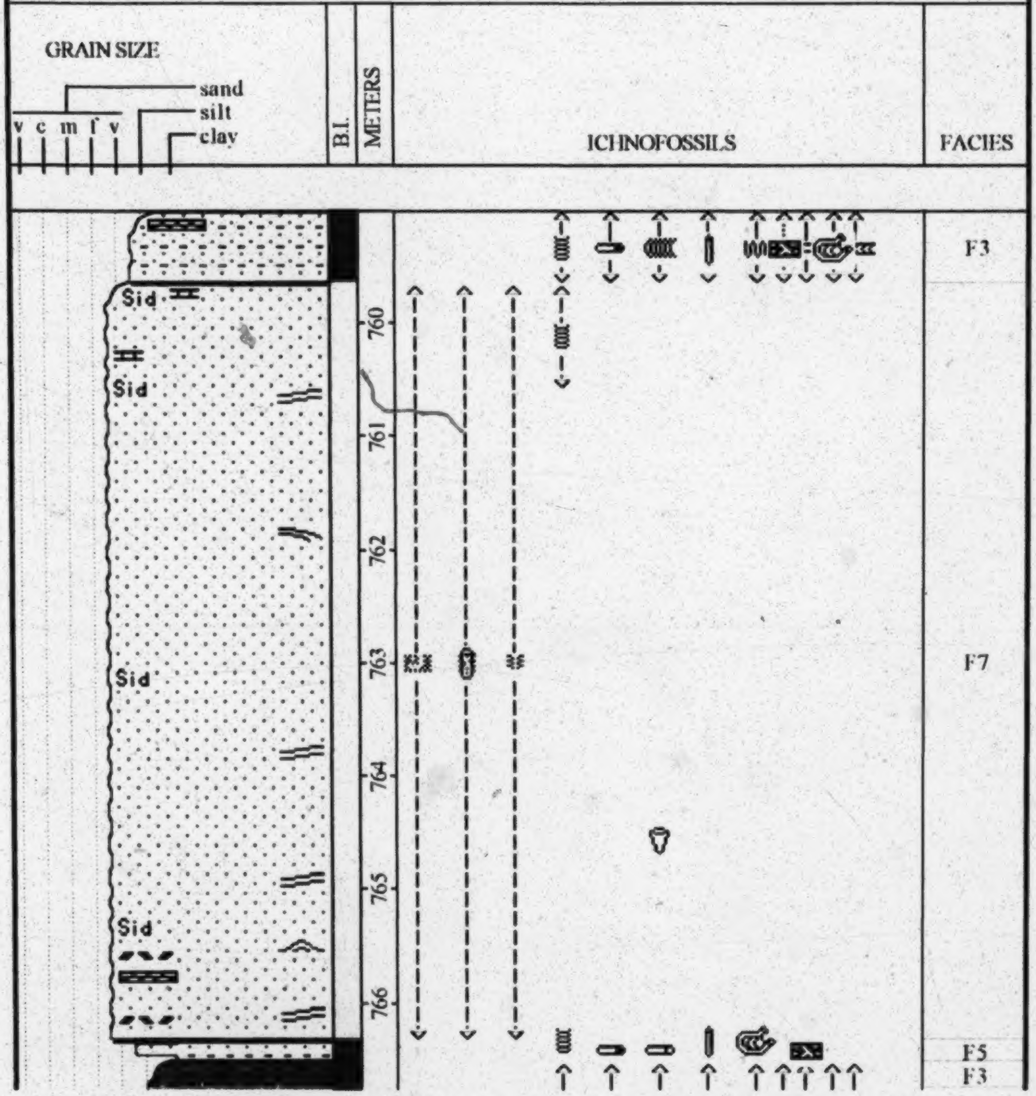

Sid
Sid
699
700
F5
F2

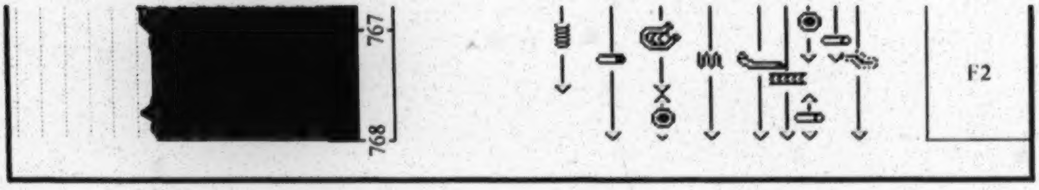
14-34-74-9w6

Date Logged: August 19, 2004

Logged by: © 2005 Scott A. Reid

Ground: 817.10 m KB: 820.60 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
Sid
760
761
762
763
764
765
766
F3
F7
F5
F3

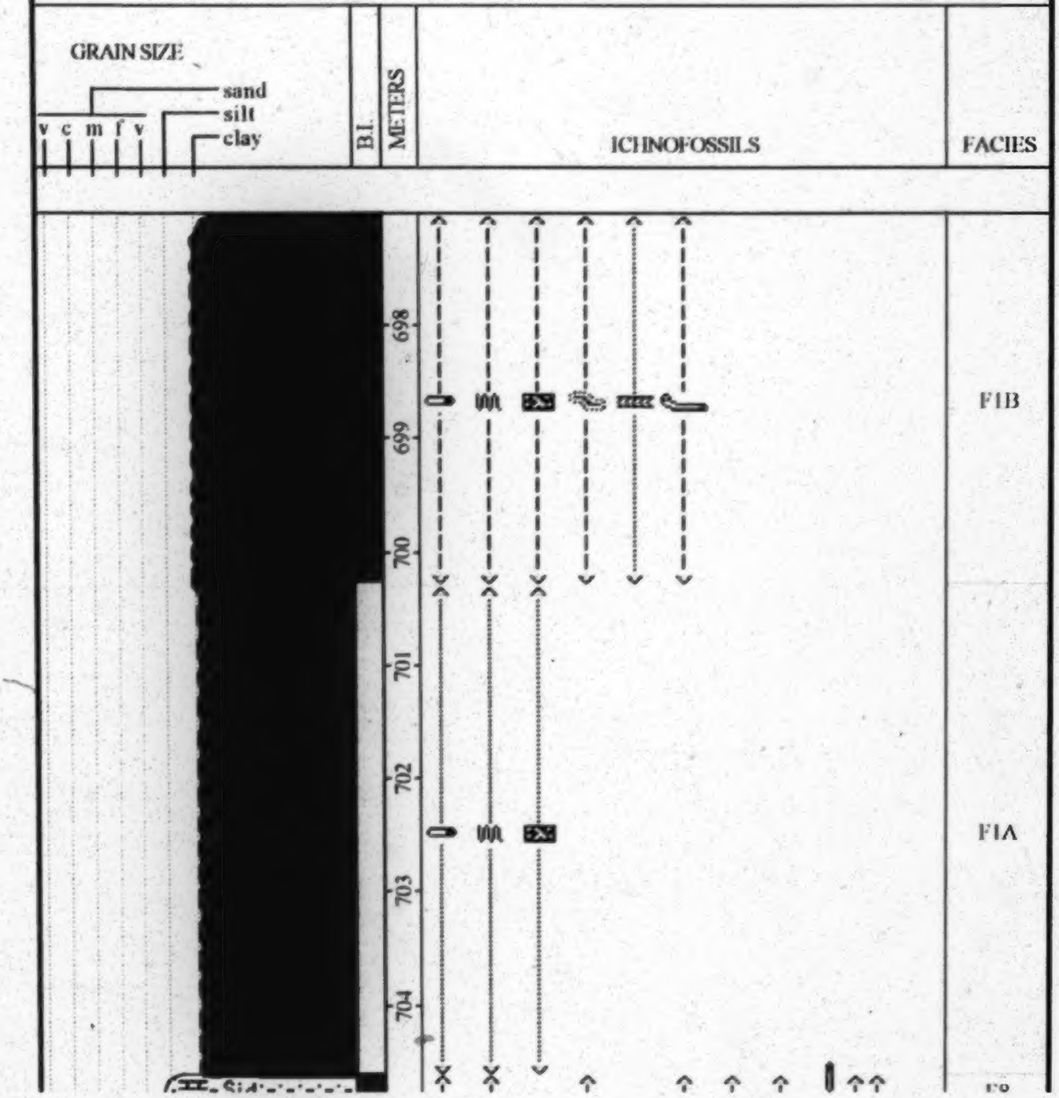

767
768
F2

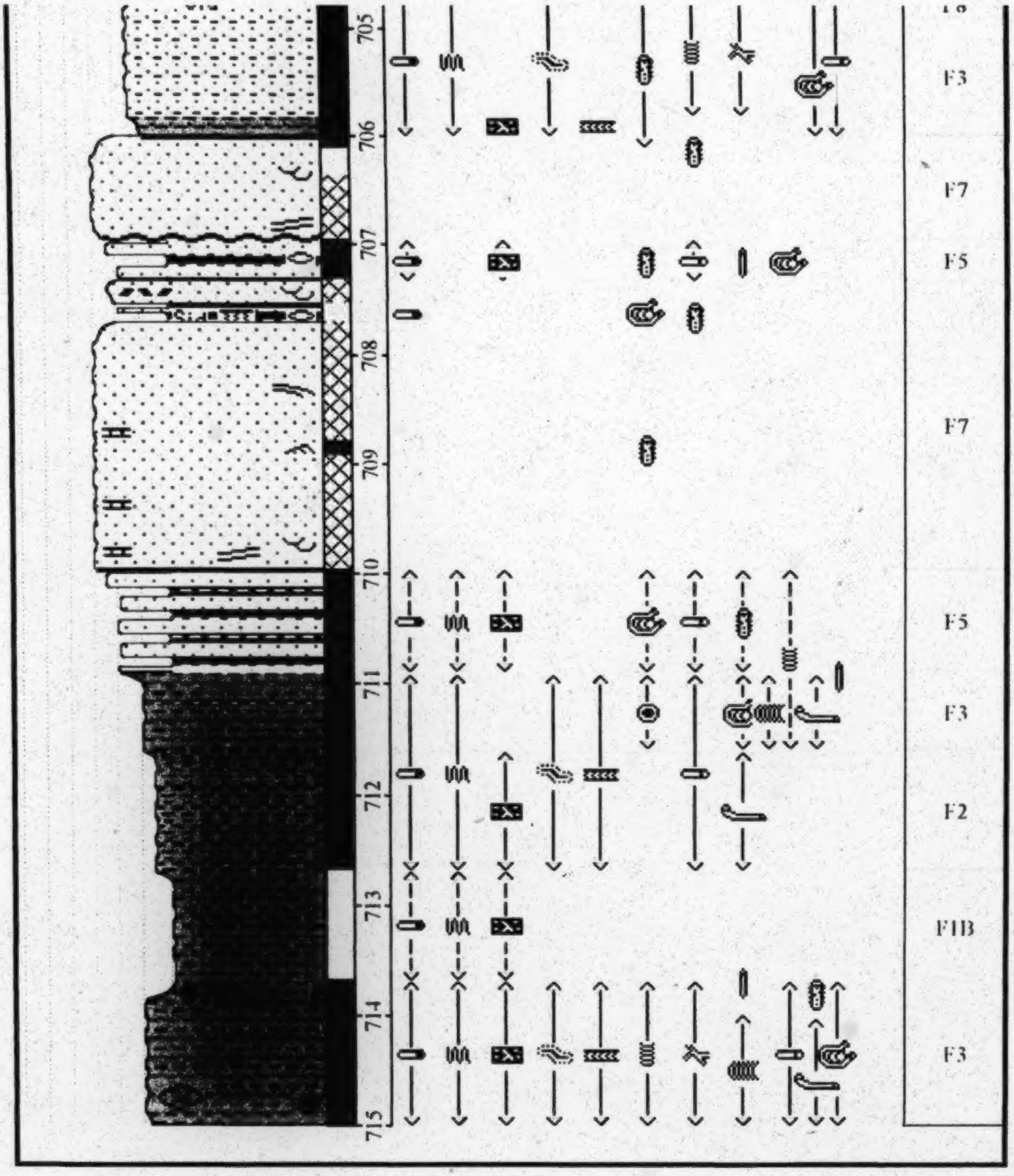
14-34-74-10w6

Date Logged: August 8, 2003

Logged by: © 2005 Scott A. Reid

Ground: 752.10 m KB: 756.40 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
698
699
700
701
702
703
704
F1B
F1A


705
706
707
708
709
710
711
712
713
714
715
F3
F7
F5
F7
F5
F3
F2
F1B
F3

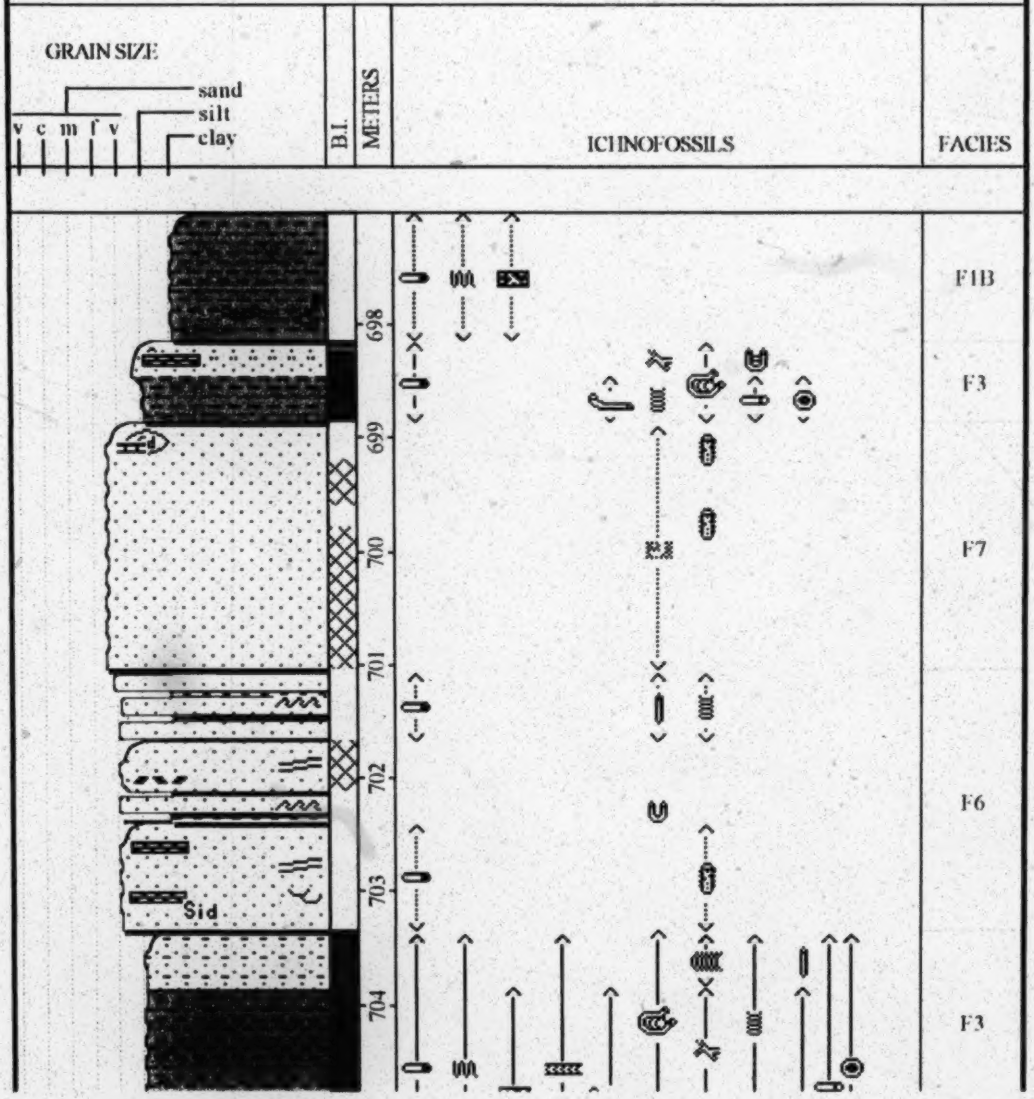
14-35-74-10w6

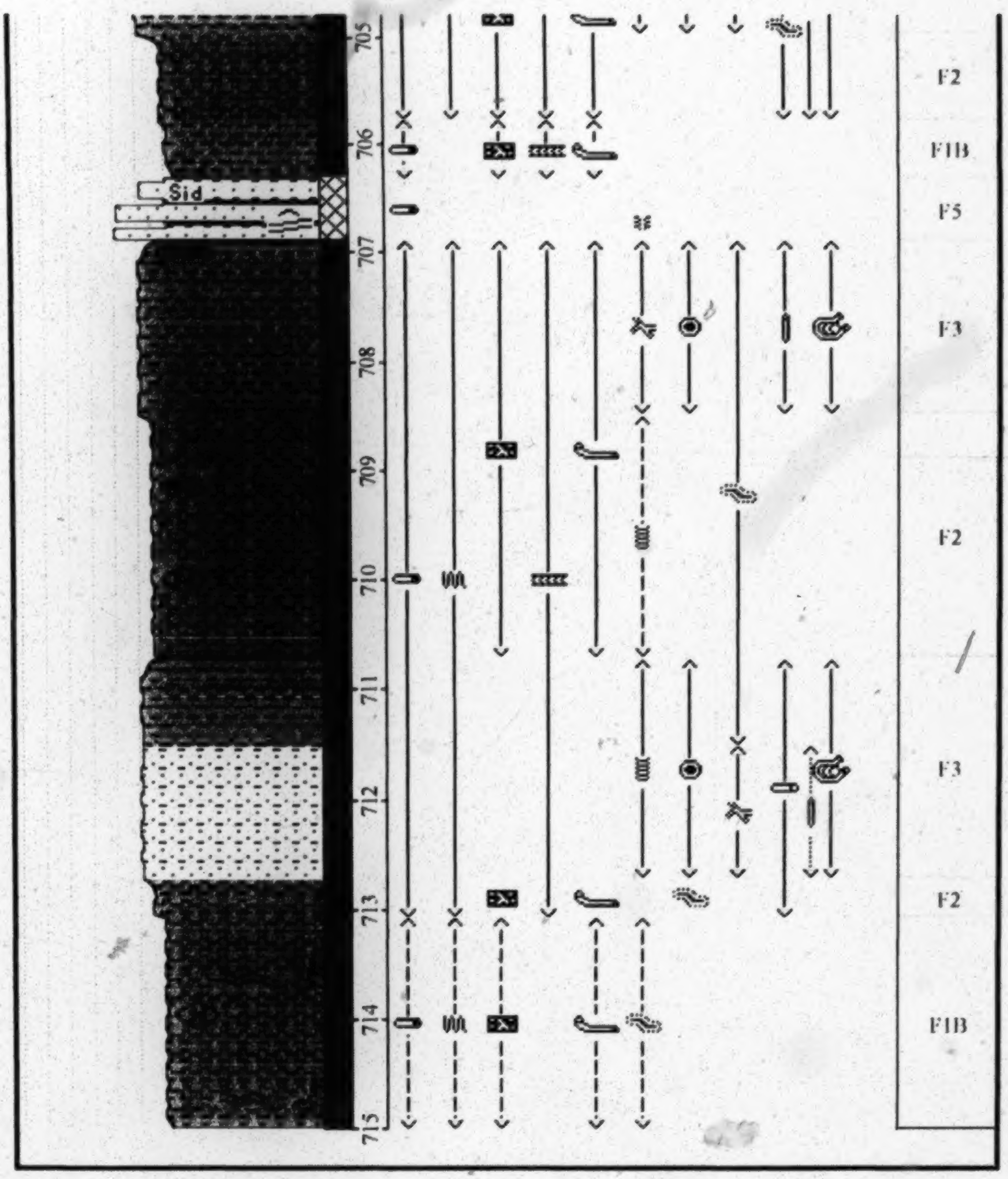
Date Logged: June 16, 2004

Logged by: © 2005 Scott A. Reid

Ground: 755.00 m KB: 759.20 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
698
699
700
701
702
703
704
Sid
F1B
F3
F7
F6
F3


705
706
707
708
709
710
711
712
713
714
715
Sid
F2
F1B
F5
F3
F2
F3
F2
F1B

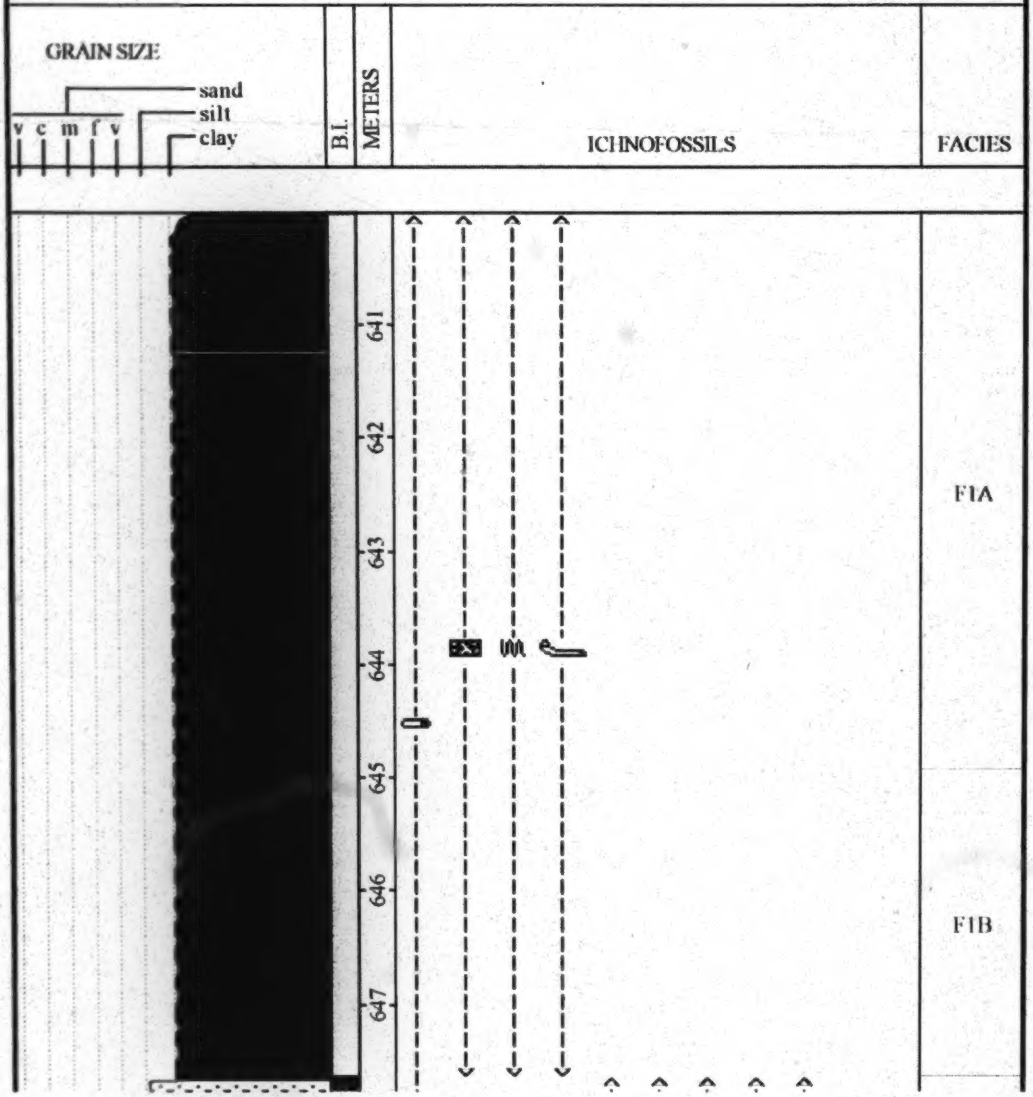
16-11-76-8w6

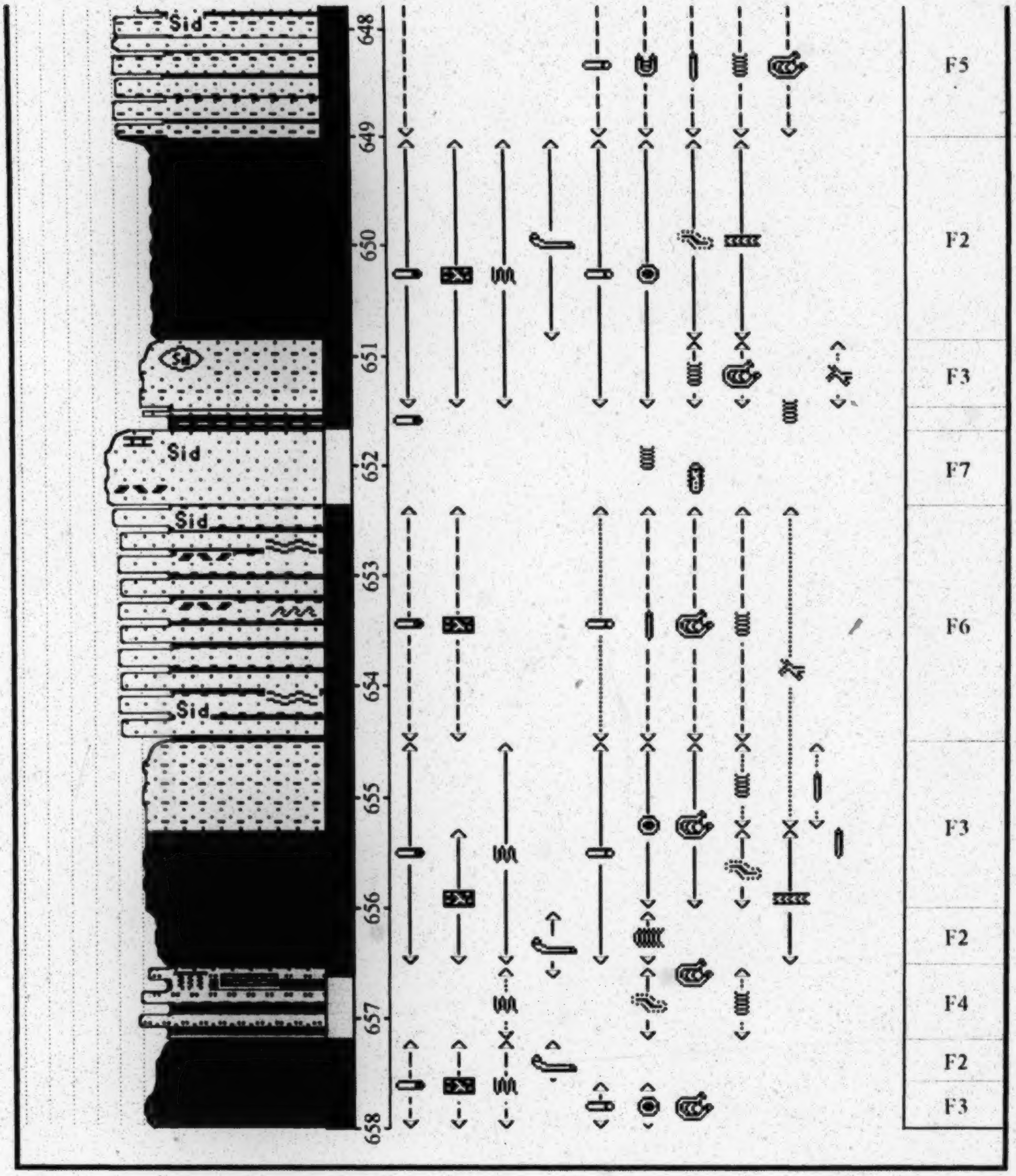
Date Logged: June 17, 2003

Logged by: © 2004 Scott A. Reid

Ground: 846.20 m KB: 849.20 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v
c
m
f
v
B.I.
METERS
ICHNOFOSSILS
FACIES
641
642
643
644
645
646
647
F1A
F1B


Sid
Sd
Sid
Sid
Sid
648
649
650
651
652
653
654
655
656
657
658
F5
F2
F3
F7
F6
F3
F2
F4
F2
F3

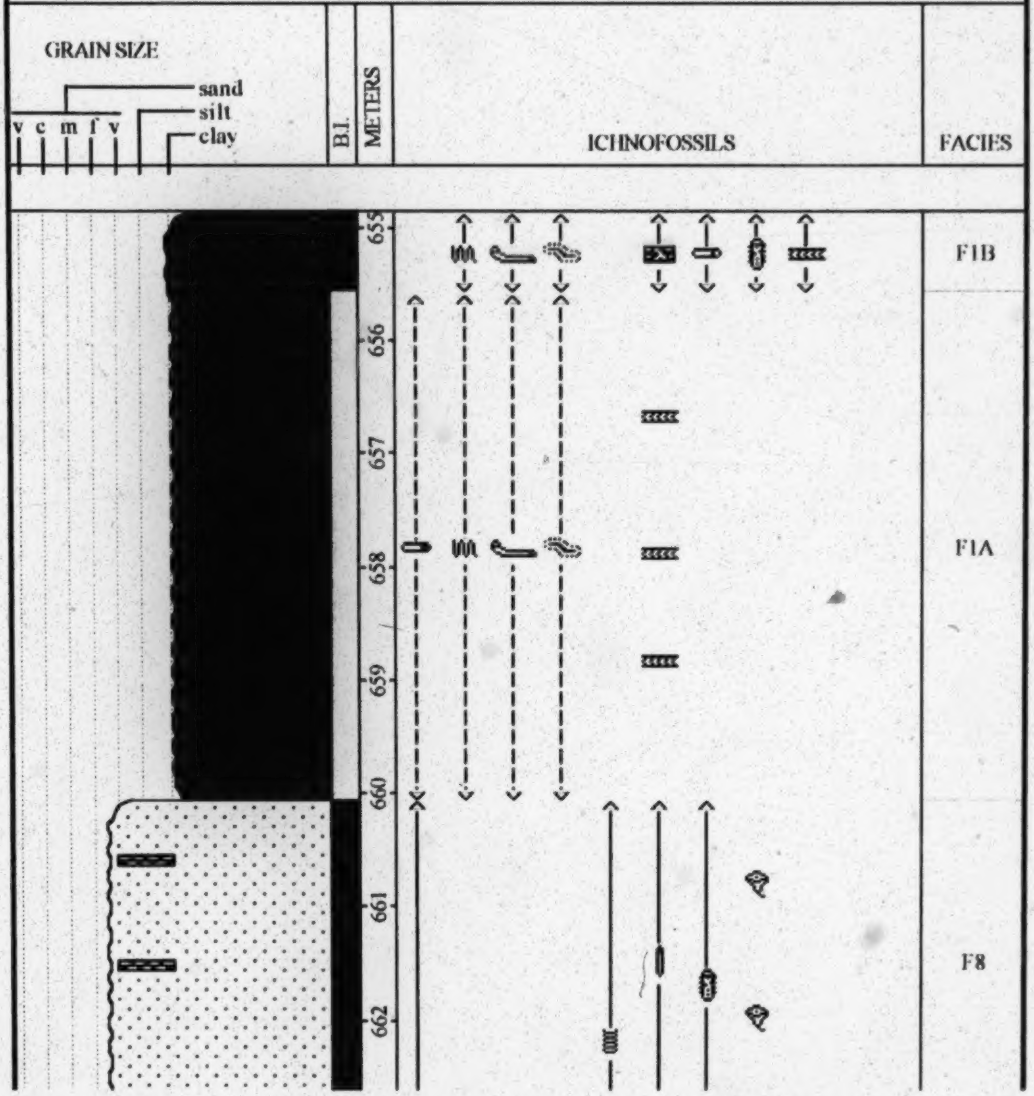
16-11-76-11w6

Date Logged: June 18, 2004

Logged by: © 2005 Scott A. Reid

Ground: 842.40 m KB: 846.70 m

Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
655
656
657
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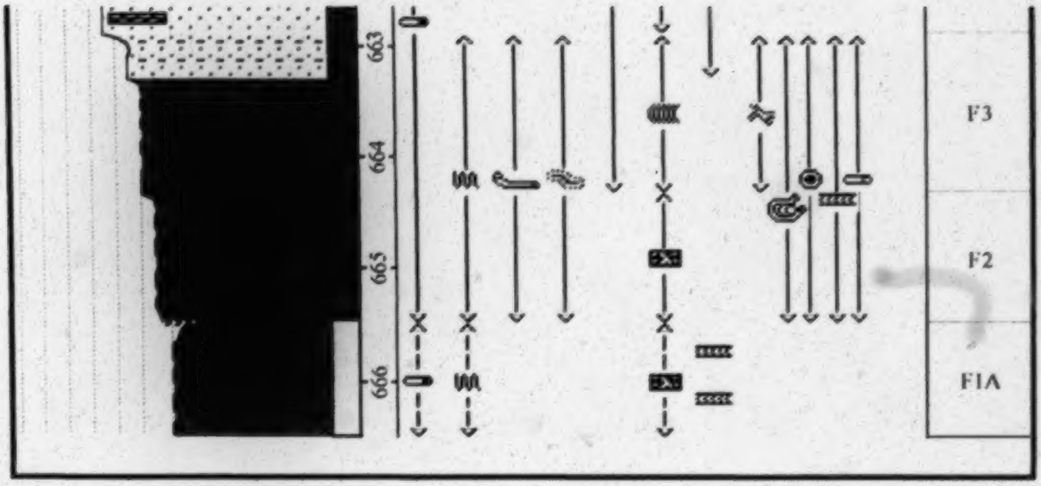
659
660
661
662
F1B
F1A
F8


663
664
665
666
F3
F2
F1A

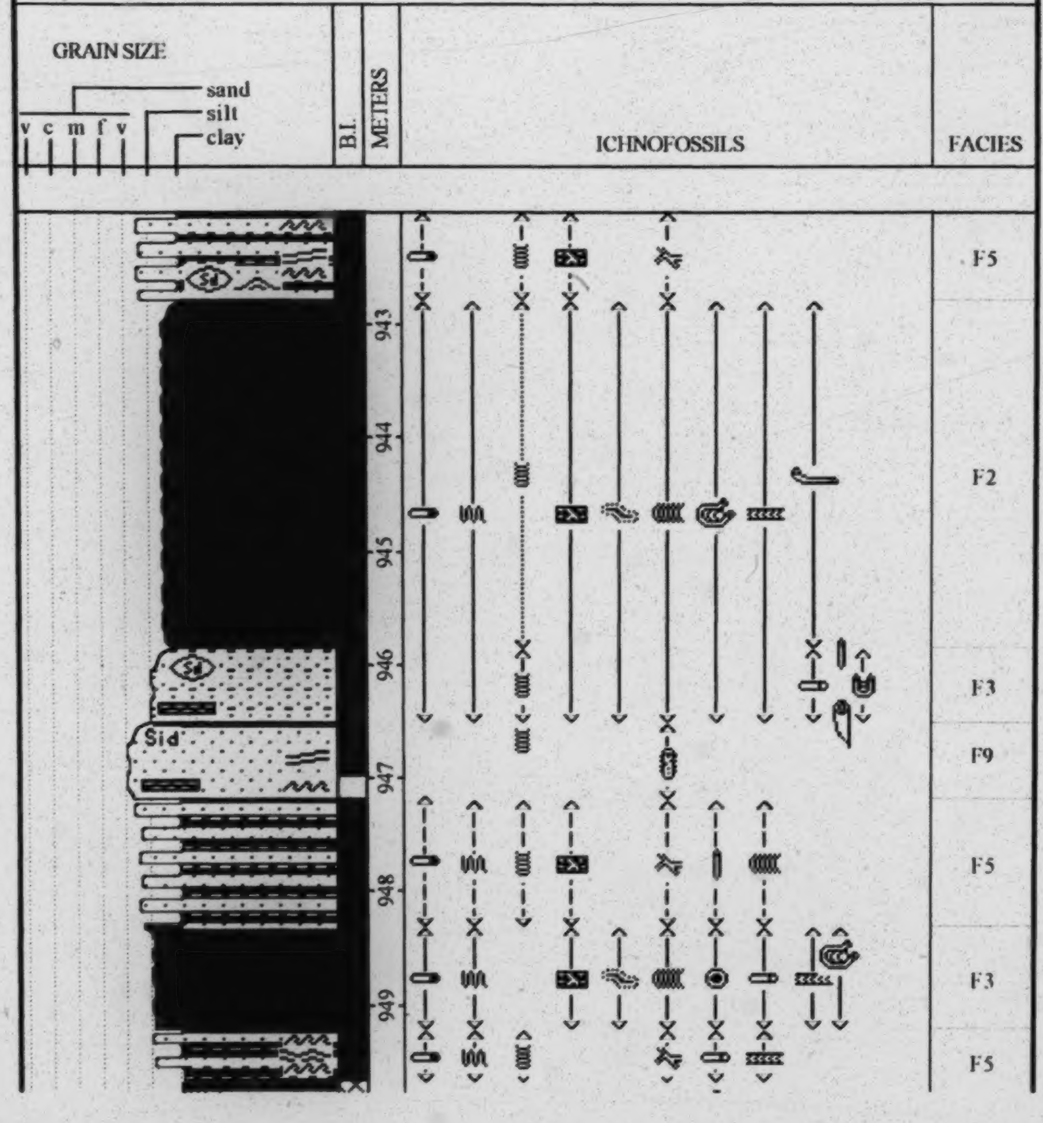
16-12-73-11w6

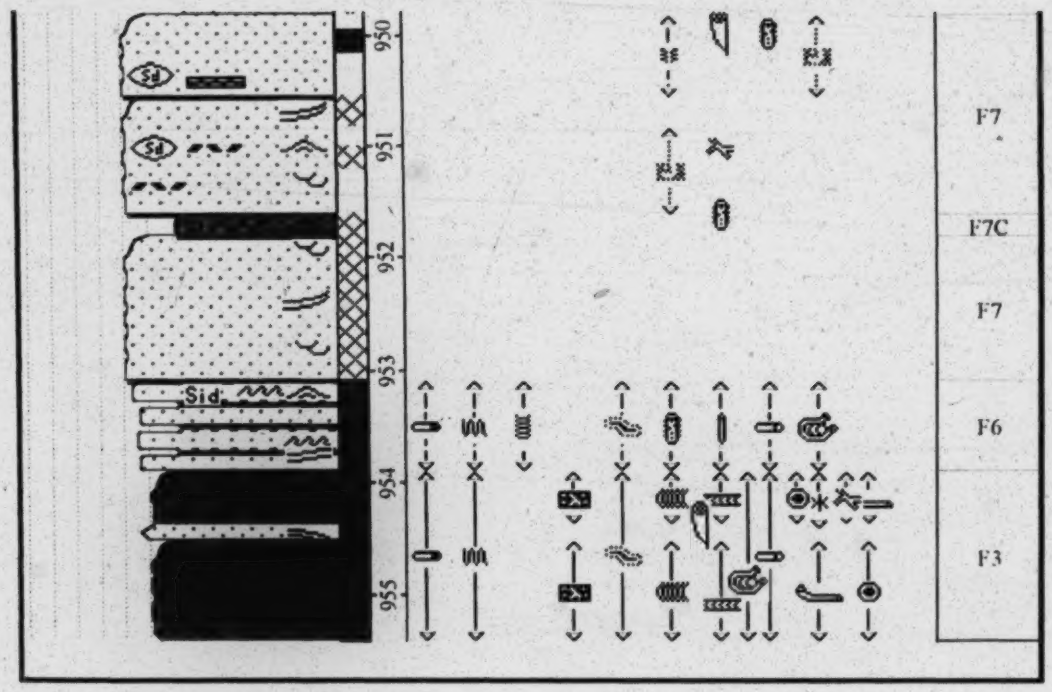
Date Logged: July 31, 2003

Logged by: © 2005 Scott A. Reid

Ground: 742.60 m KB: 747.80 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
Sd
943
944
945
946
Sd
Sid
947
948
949
F5
F2
F3
F9
F5
F3
F5


950
951
952
953
954
955
Sd
Sd
Sid
F7
F7C
F7
F6
F3

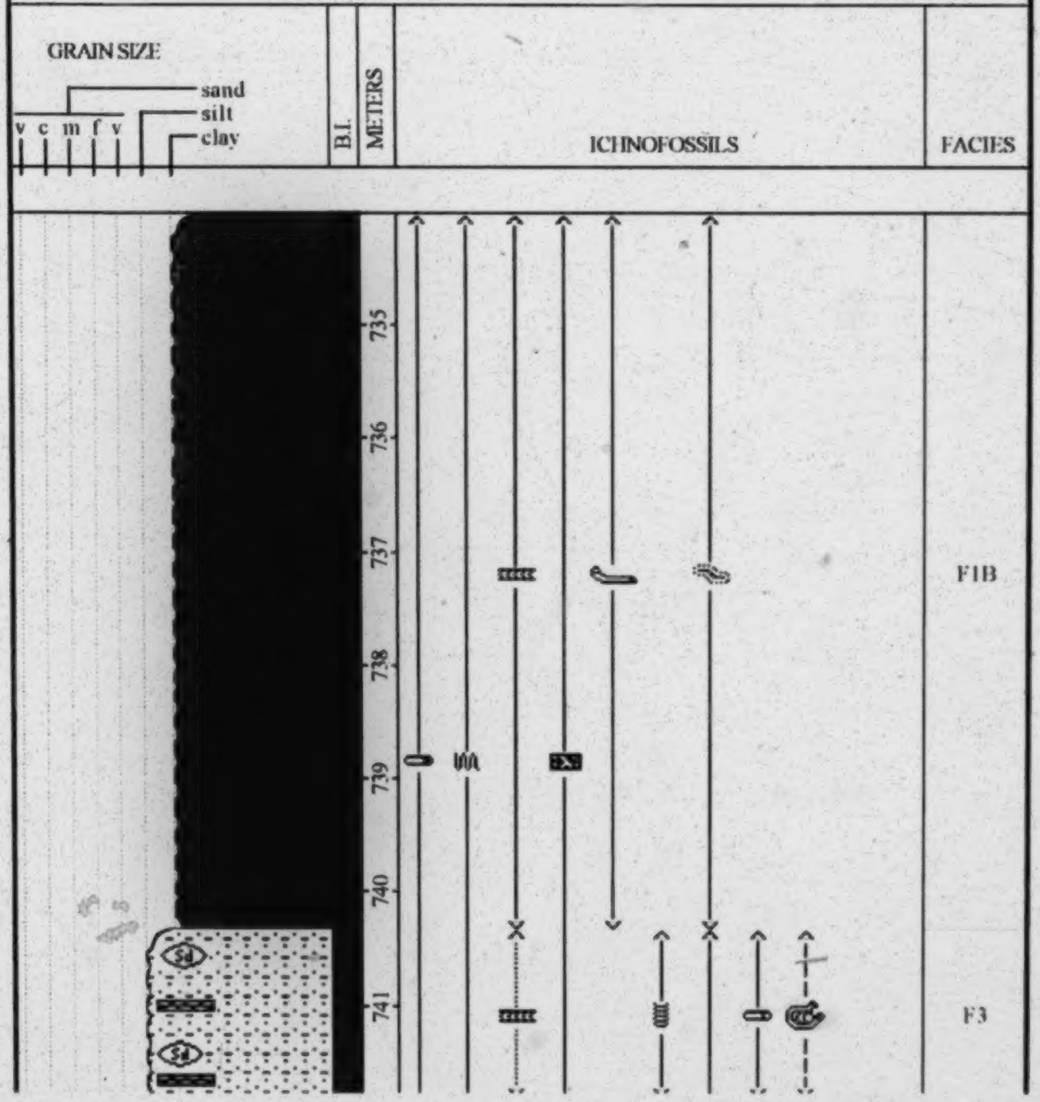
16-22-75-8w6

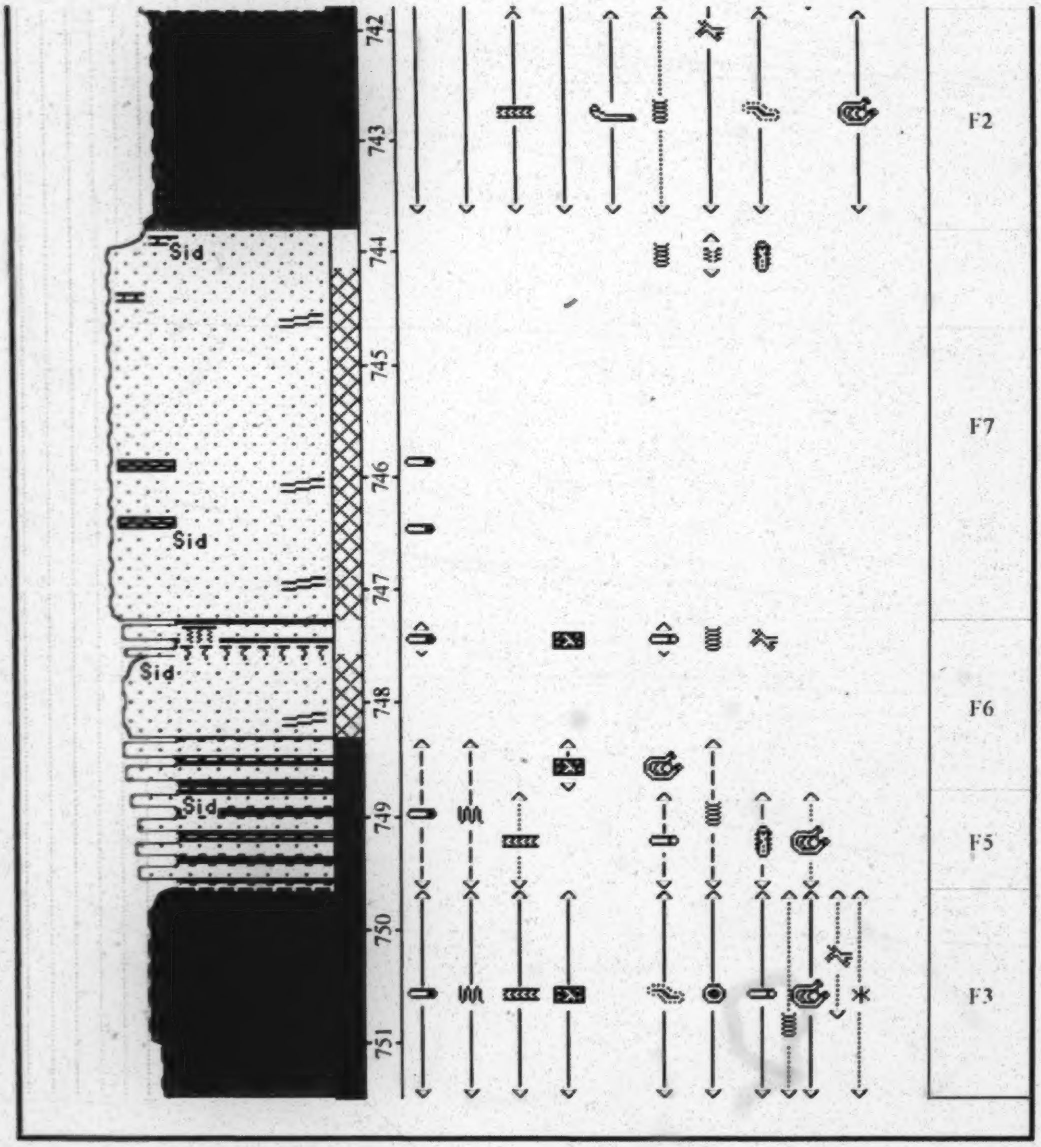
Date Logged: June 17, 2004

Logged by: © 2005 Scott A. Reid

Ground: 904.60 m   KB: 907.60 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
735
736
737
738
739
740
741
F1B
F3
Sd
Sd

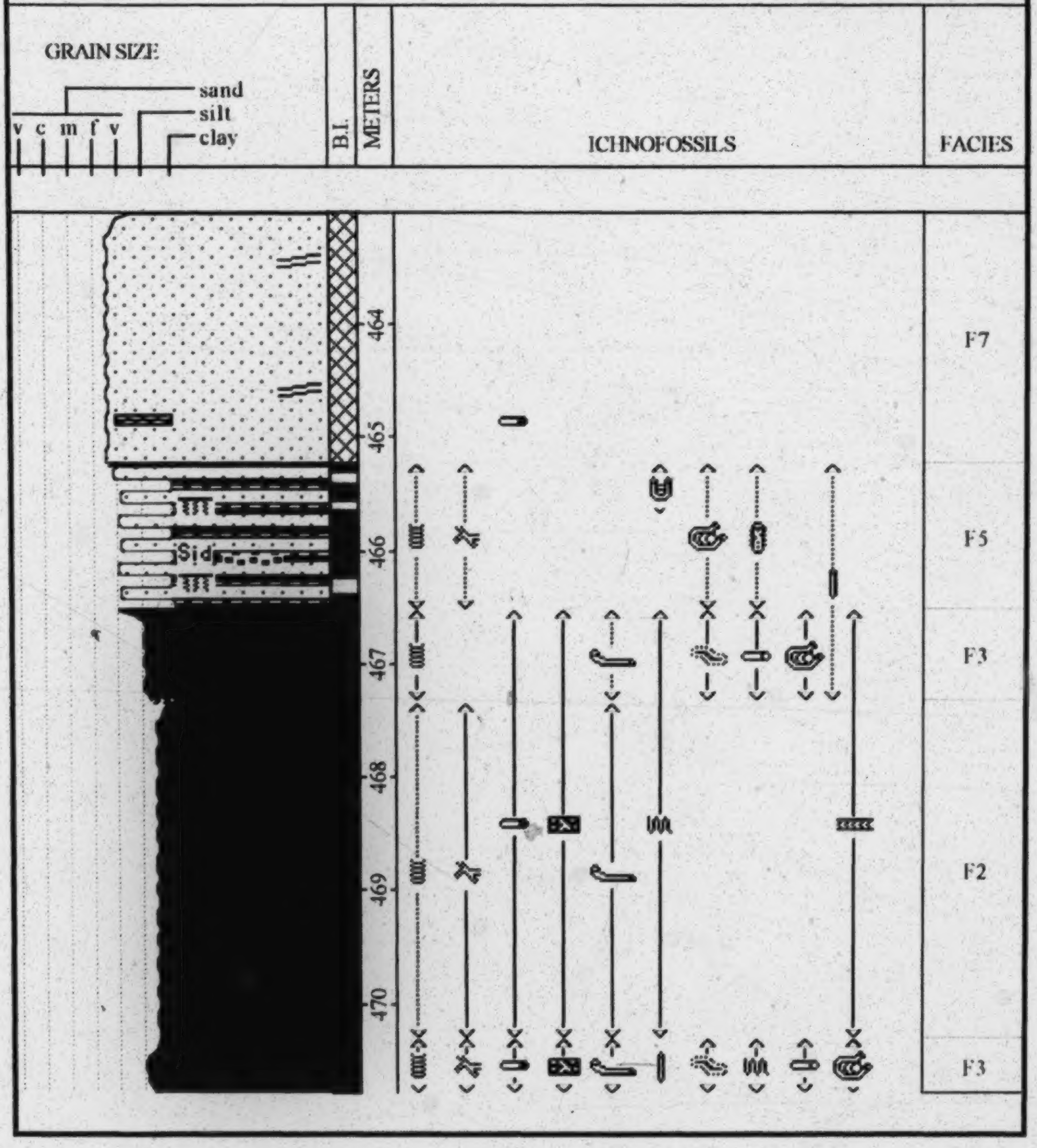

742
743
744
745
746
747
748
749
750
751
Sid
Sid
Sid
Sid
F2
F7
F6
F5
F3

16-28-77-13w6

Date Logged: June 23, 2004

Logged by: © 2005 Scott A. Reid

Ground: 842.80 m KB: 846.10 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
Sid
464
465
466
467
468
469
470
F7
F5
F3
F2
F3

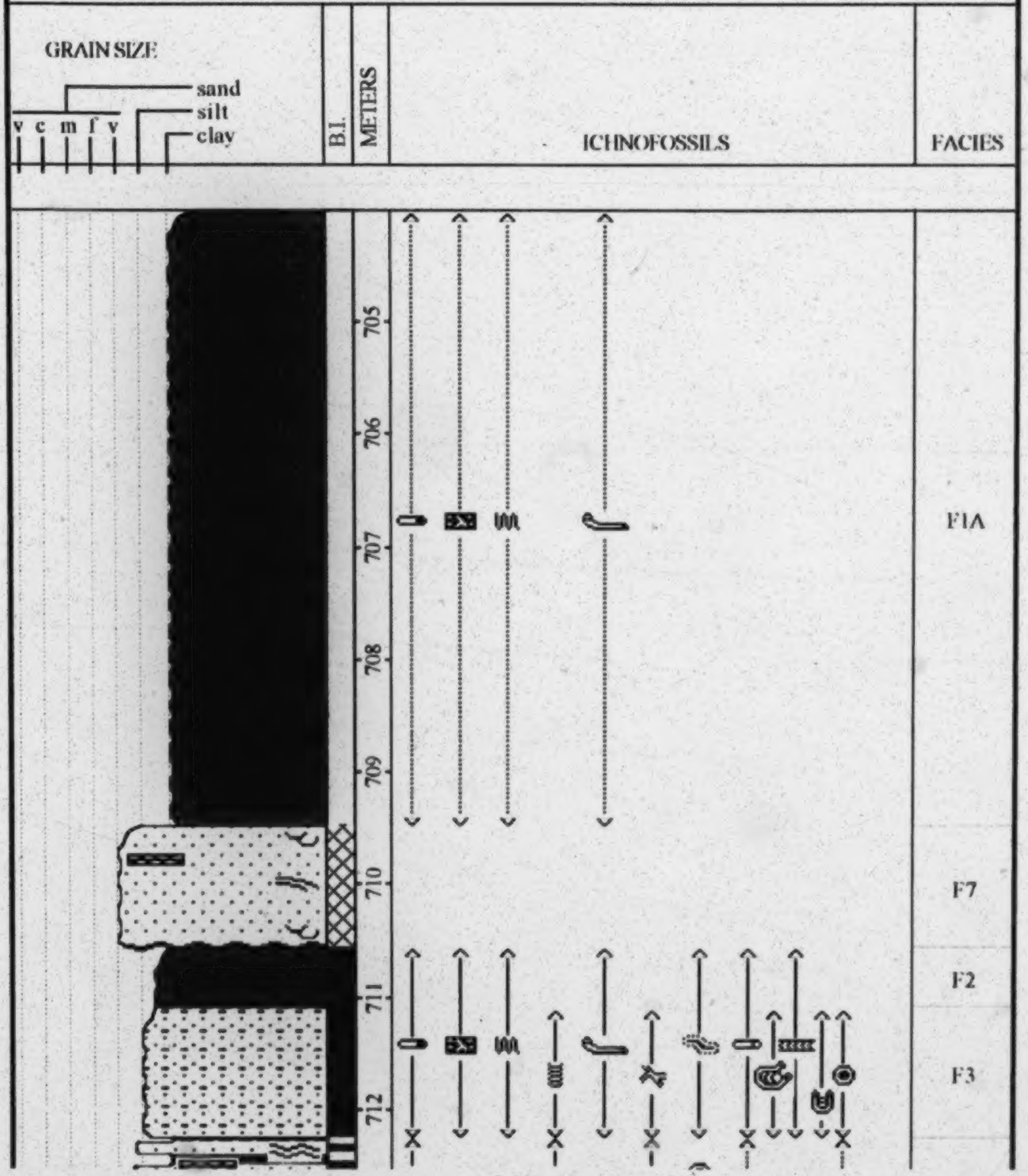
16-29-74-9w6

Date Logged: August 14, 2003

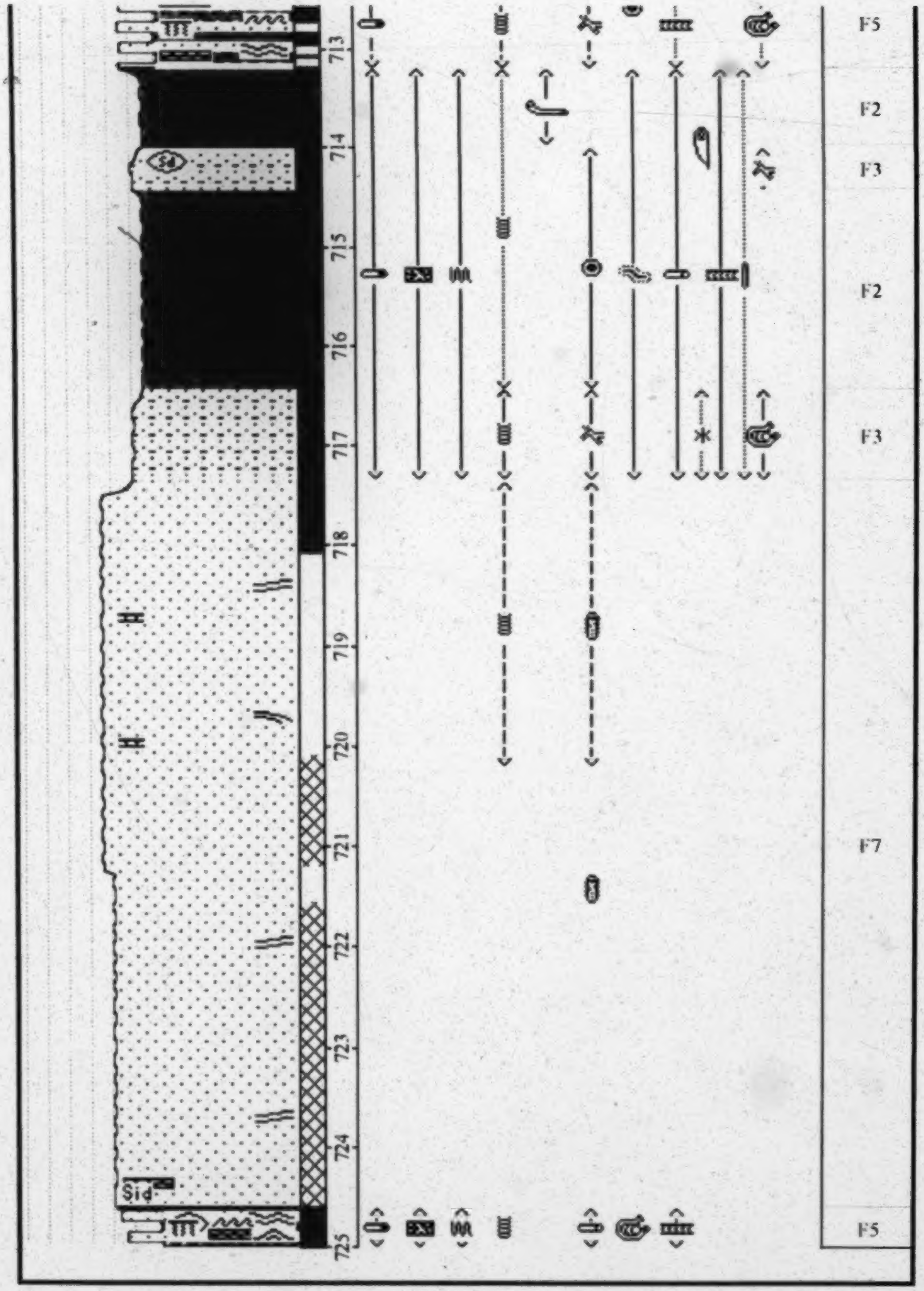
Logged by: © 2005 Scott A. Reid

Ground: 765.40 m KB: 768.90 m

I.R.G. Ichnology Research Group



GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
705
706
707
708
709
710
711
712
F1A
F7
F2
F3

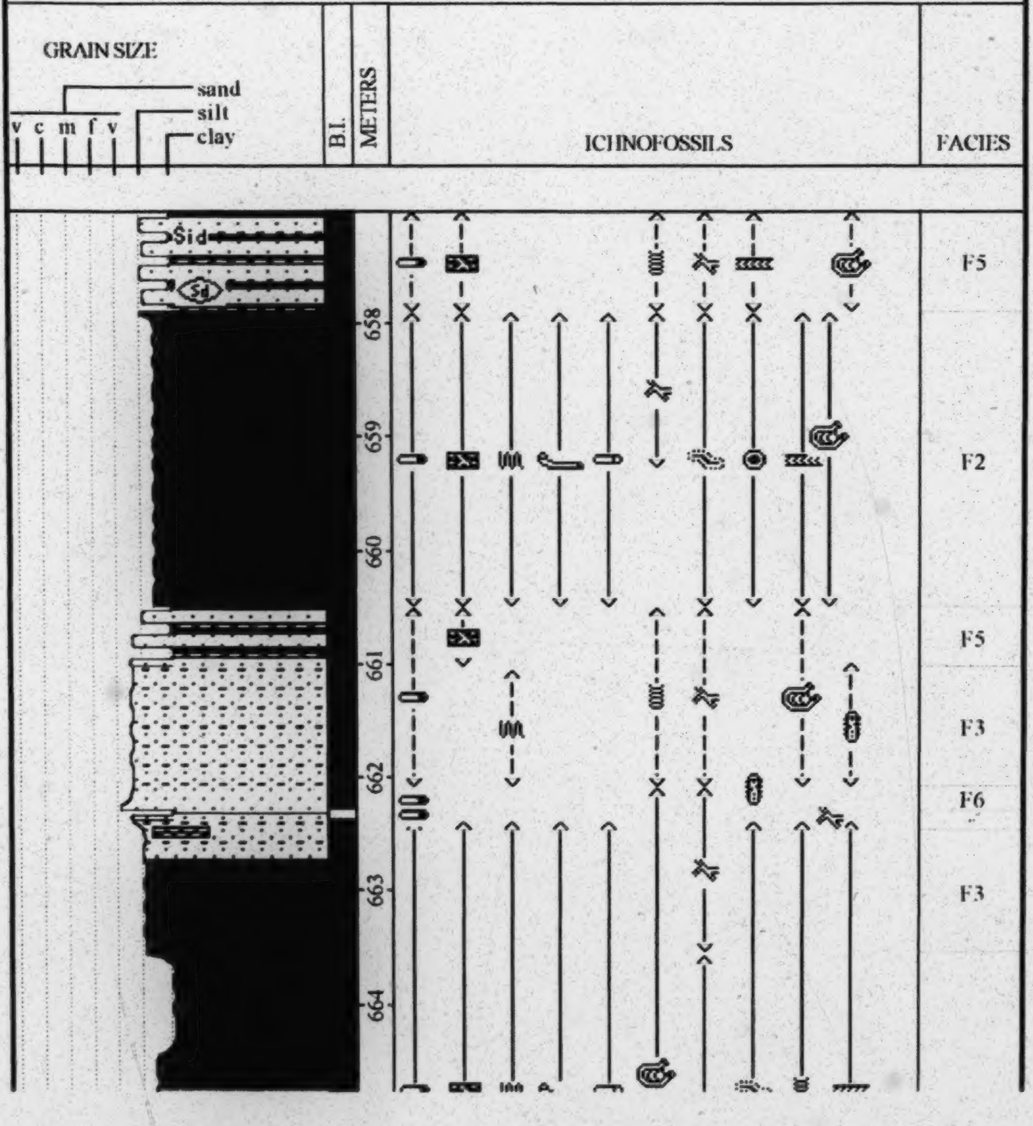

713
714
715
716
717
718
719
720
721
722
723
724
725
Sd
Sid
F5
F2
F3
F2
F3
F7
F5

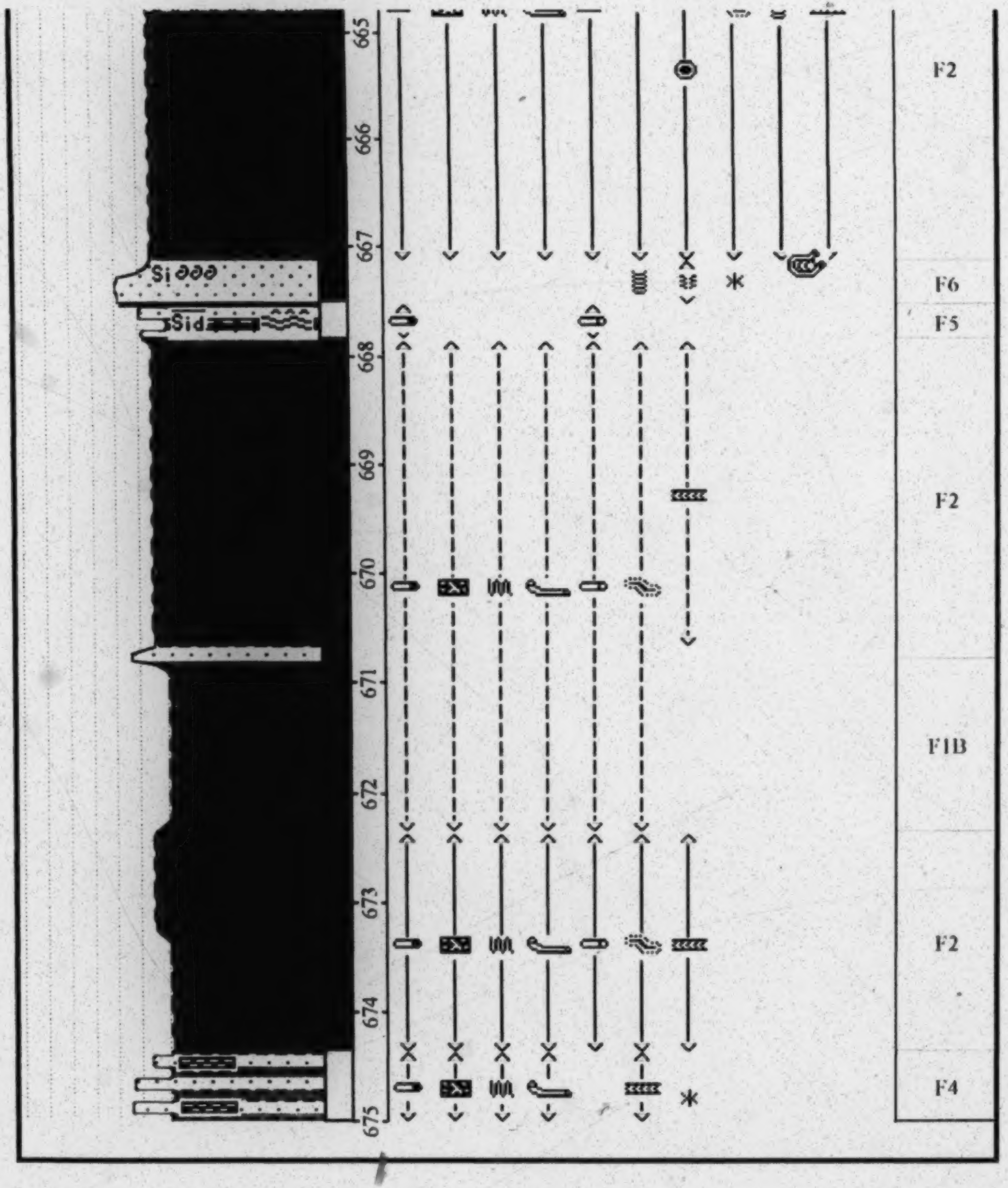
16-34-76-9w6

Date Logged: June 23, 2003

Logged by: © 2005 Scott A. Reid

Ground: 894.20 m KB: 897.60 m


GRAIN SIZE
v c m f v
sand
silt
clay
B.I.
METERS
ICHNOFOSSILS
FACIES
Sid
Sd
658
659
660
661
662
663
664
F5
F2
F5
F3
F6
F3


665
666
667
668
669
670
671
672
673
674
675
Si
Sid
F2
F6
F5
F2
F1B
F2
F4

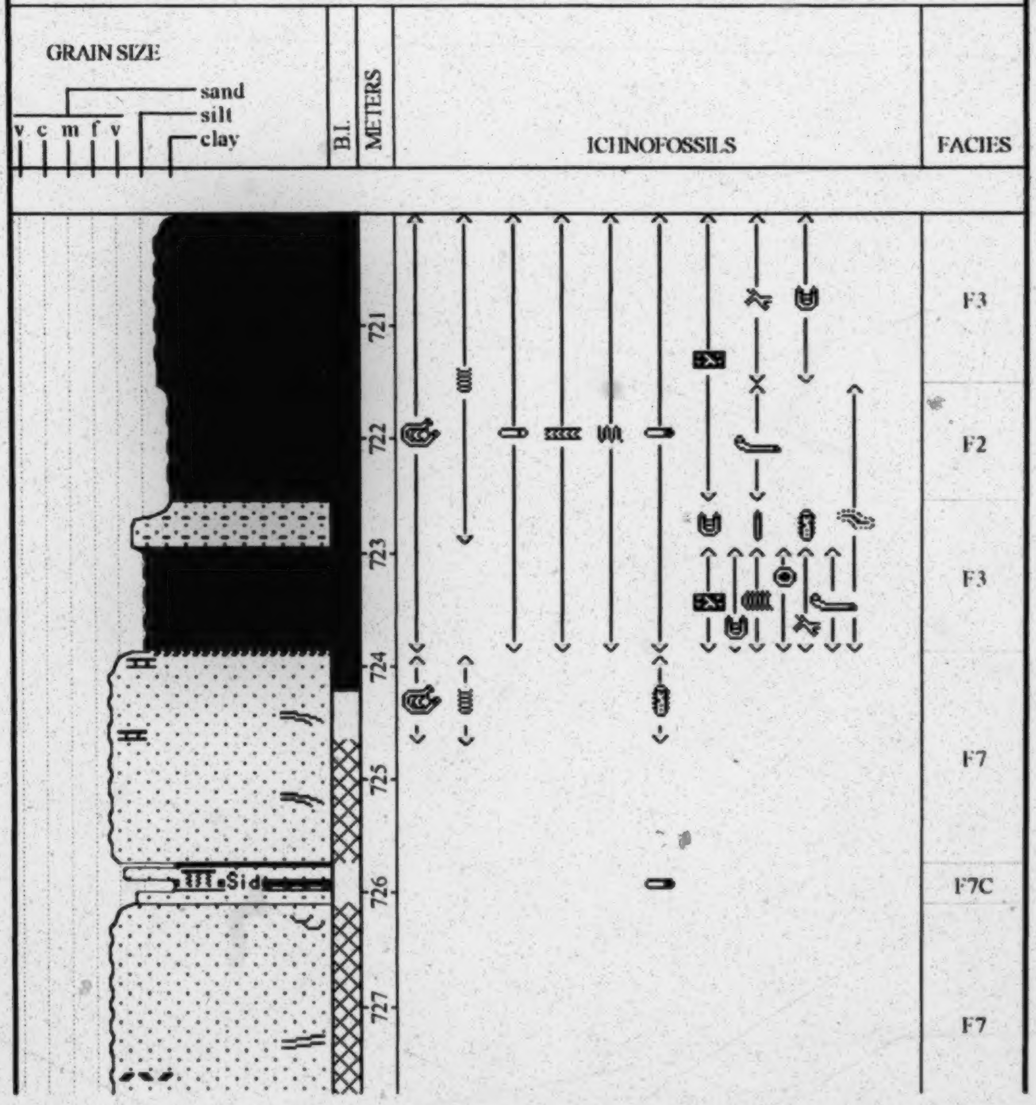
16-35-74-9w6

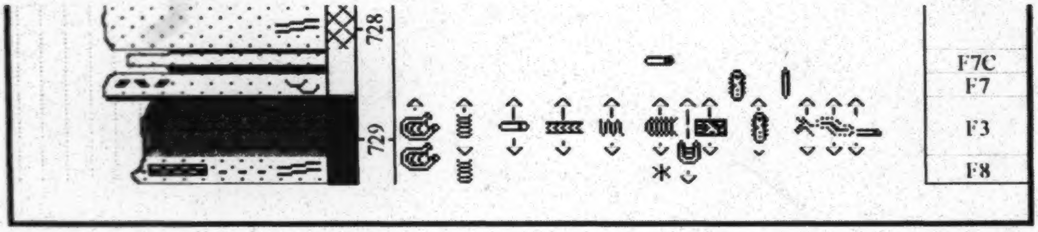
Date Logged: August 19, 2003

Logged by: © 2005 Scott A. Reid

Ground: 779.80 m KB: 783.20 m

I.R.G.
Ichnology Research Group


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
721
722
723
724
725
726
727
Sid
F3
F2
F3
F7
F7C
F7

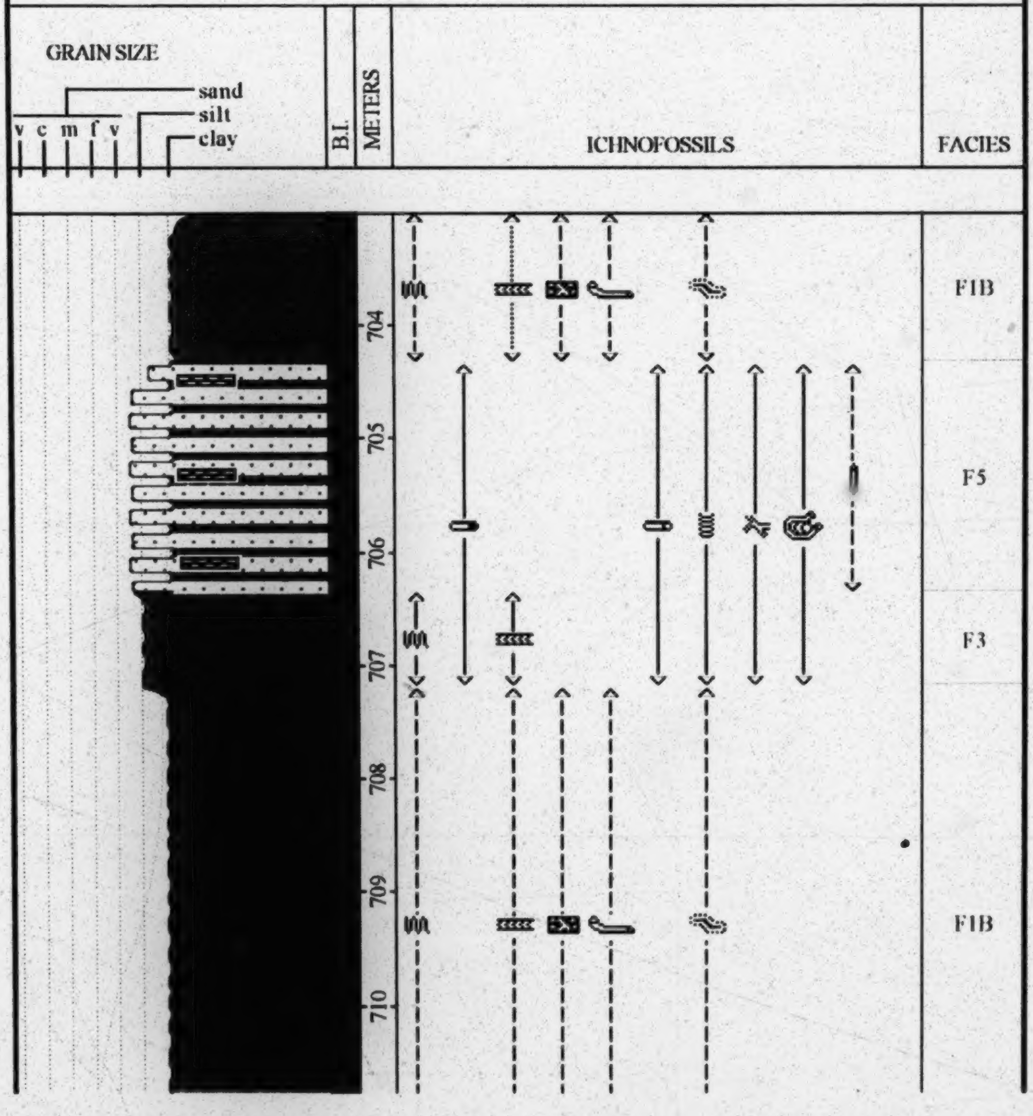

728
729
F7C
F7
F3
F8

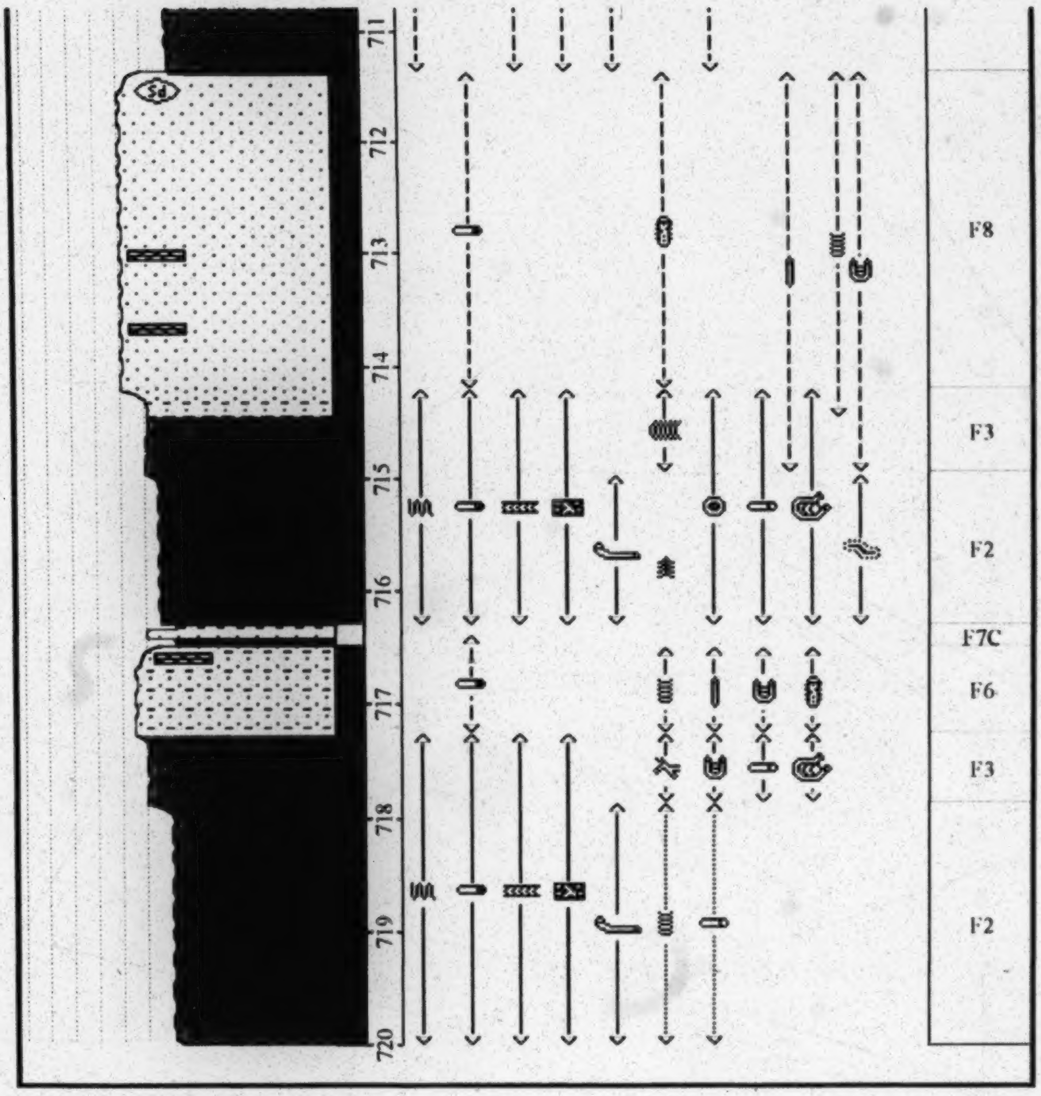
16-35-75-11w6

Date Logged: July 18, 2003

Logged by: © 2005 Scott A. Reid

Ground: 853.60 m KB: 856.60 m


GRAIN SIZE
sand
silt
clay
v c m f v
B.I.
METERS
ICHNOFOSSILS
FACIES
704
705
706
707
708
709
710
F1B
F5
F3
F1B


Sd
711
712
713
714
715
716
717
718
719
720
F8
F3
F2
F7C
F6
F3
F2